Neuromechanics and Spinal Cord: Muscle and Motor Unit Redundancy

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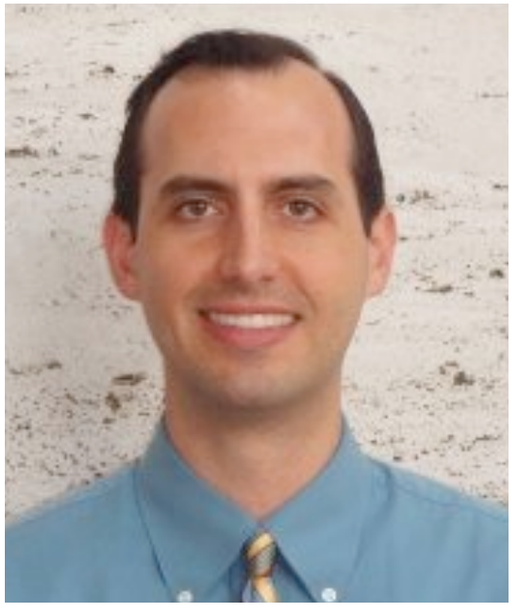
Louise Cosand



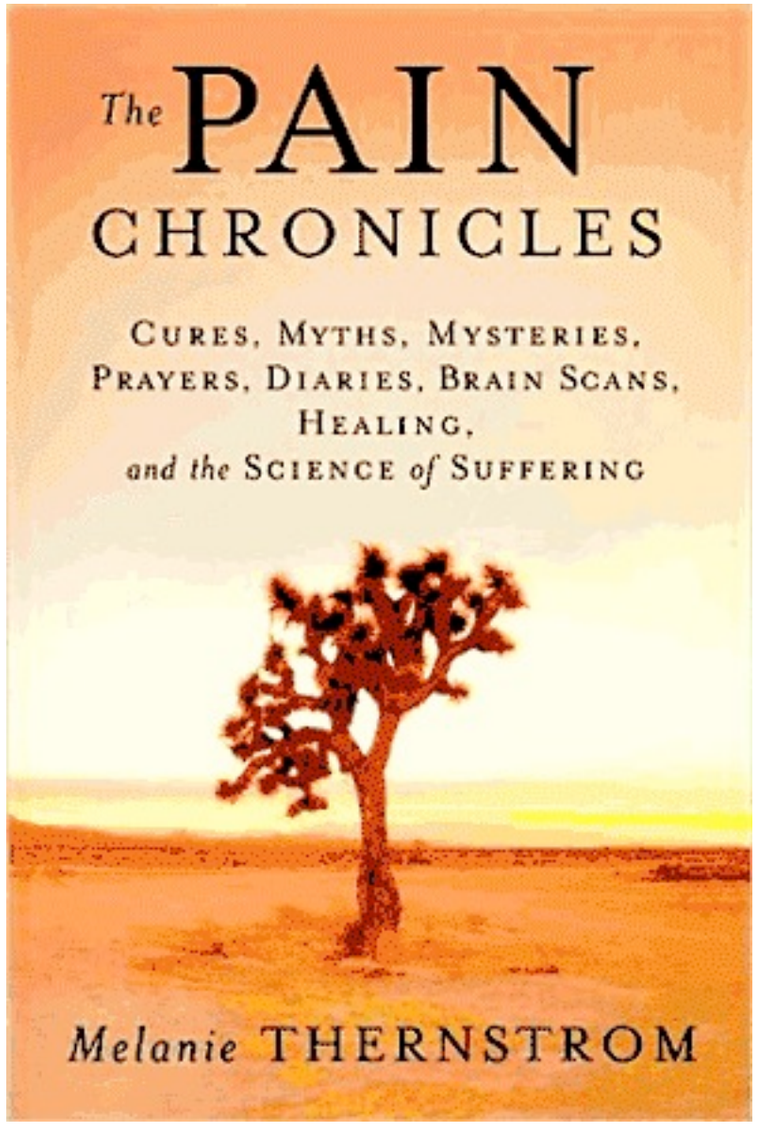
Dan Kirages, DPT

Moheb Yani

Overview

- Biomechanics to Brain Pain
- Muscle Redundancy
- Motor Unit Redundancy
- Think computation, act experimentation

Biomechanics to Brain Pain



Chronic pain: pain that extends beyond the expected period of healing[1]

[1]Turk and Okifuji, 2001

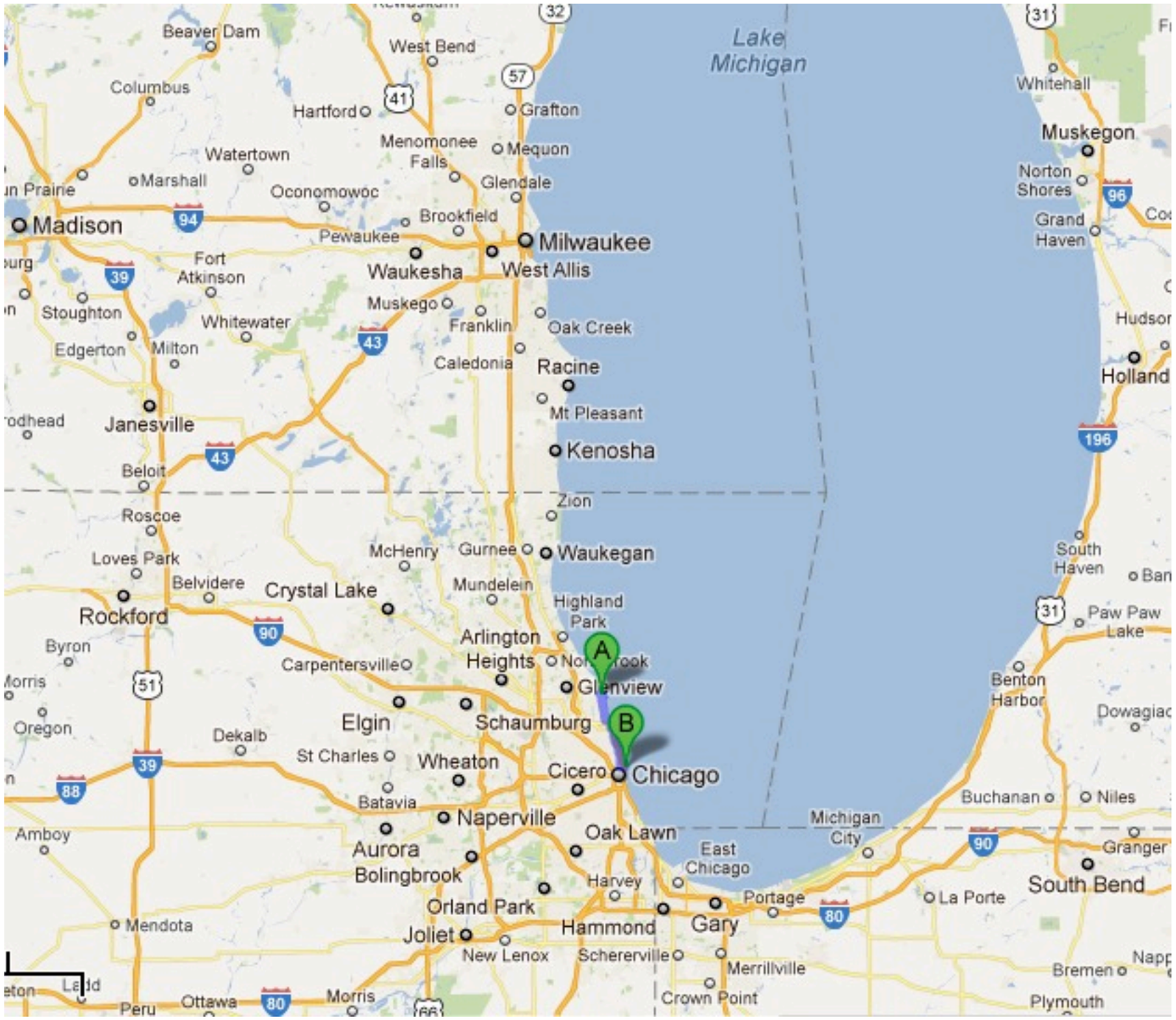
My Ph.D. training was interdisciplinary

Tony Bloch, Ph.D.
Applied Mathematics

Art Kuo, Ph.D.
Biomechanics

Zev Rymer, M.D. Ph.D.
Neurophysiology

Cycling + Stress = CP/CPPS?



Biomechanics to Brain Pain

Chronic prostatitis/chronic pelvic pain syndrome (CP/CPPS) is a clinical condition presenting as **chronic pelvic pain for 3 months** within a 6-month period, with a variable degree of **urinary and sexual dysfunction** in the **absence of any identifiable pathology**.[1]

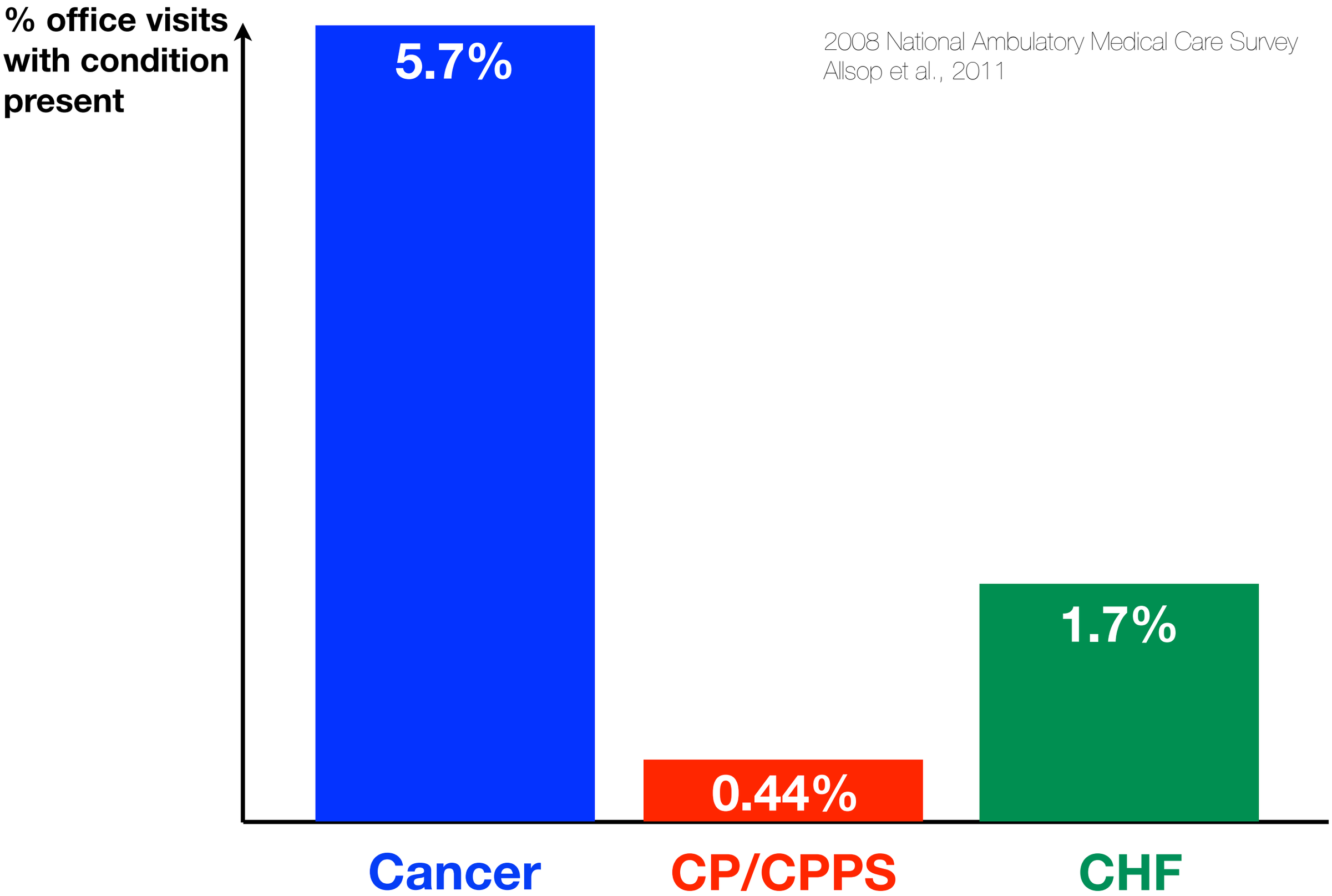
- Prevalence: 6 - 12% (Most frequent urological diagnosis for men under 50).[2]

- Virulence: Accounts for 8% of urological visits and 1% of all primary care visits. QOL scores lower than CHF, diabetes, and Crohn's disease.[2]

- Cost: $6,500 per patient per year.[2]

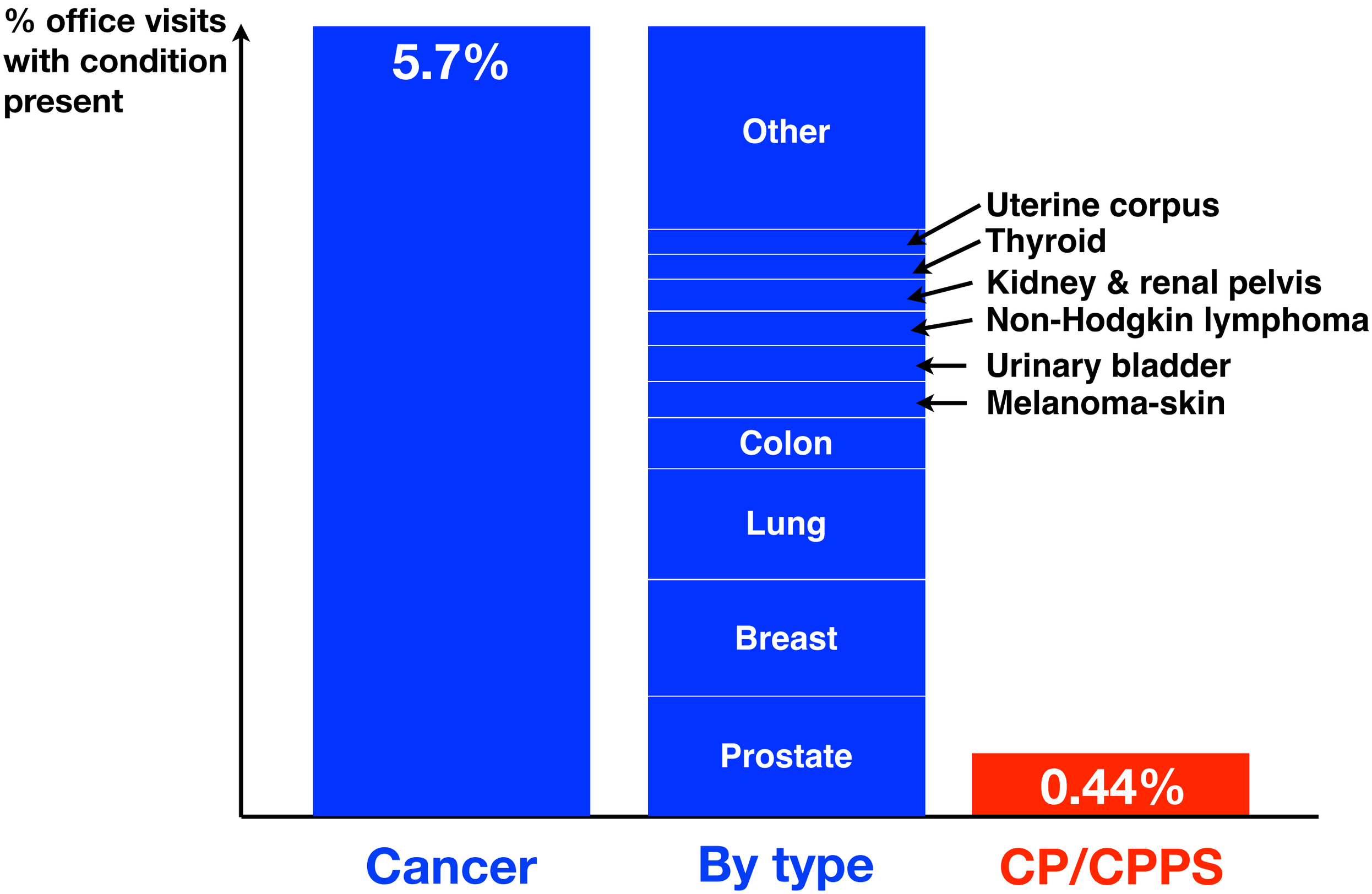
1. Krieger et al., 1999
2. Allsop et al., 2011

Biomechanics to Brain Pain



2008 National Ambulatory Medical Care Survey
Allsop et al., 2011

Biomechanics to Brain Pain

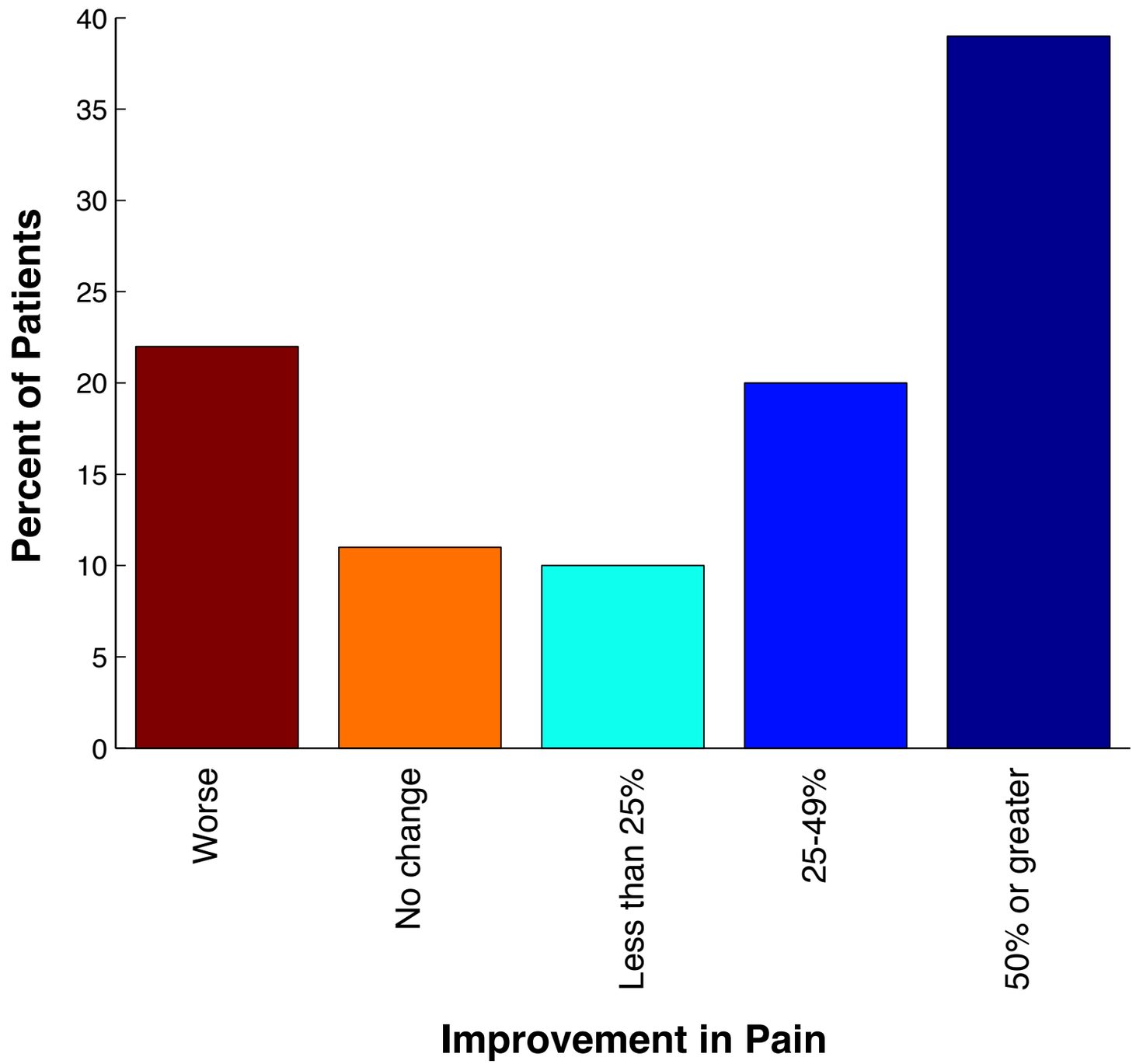


Current (conservative) Treatment Options

- Long (3 months+) course of antibiotics.[1]
- Combination of physical therapy and relaxation techniques.[2]
- Aerobic exercise.[3]

1. Allsop et al., 2011
2. Anderson et al., 2005
3. Giubilei 2007

Problem with current treatments



Anderson et al., 2005

Several approaches, little objective plan

"Out-of-tune approach"
Aerobic exercise

Giubilei et al., 2007

"In-tune approach"
Physical therapy and relaxation

Anderson et al., 2005

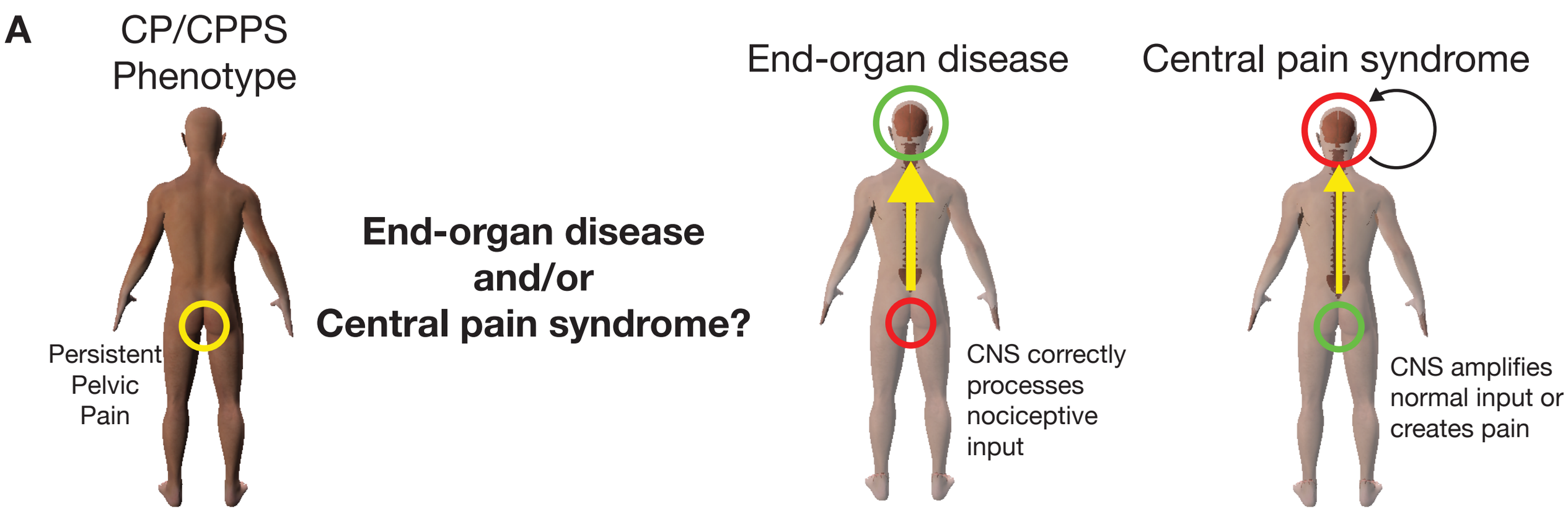
"Pharmaceutical approach"
Alpha-blockers, tricyclic anti-depressants, etc.

Allsop et al., 2011

Biomechanics to Brain Pain

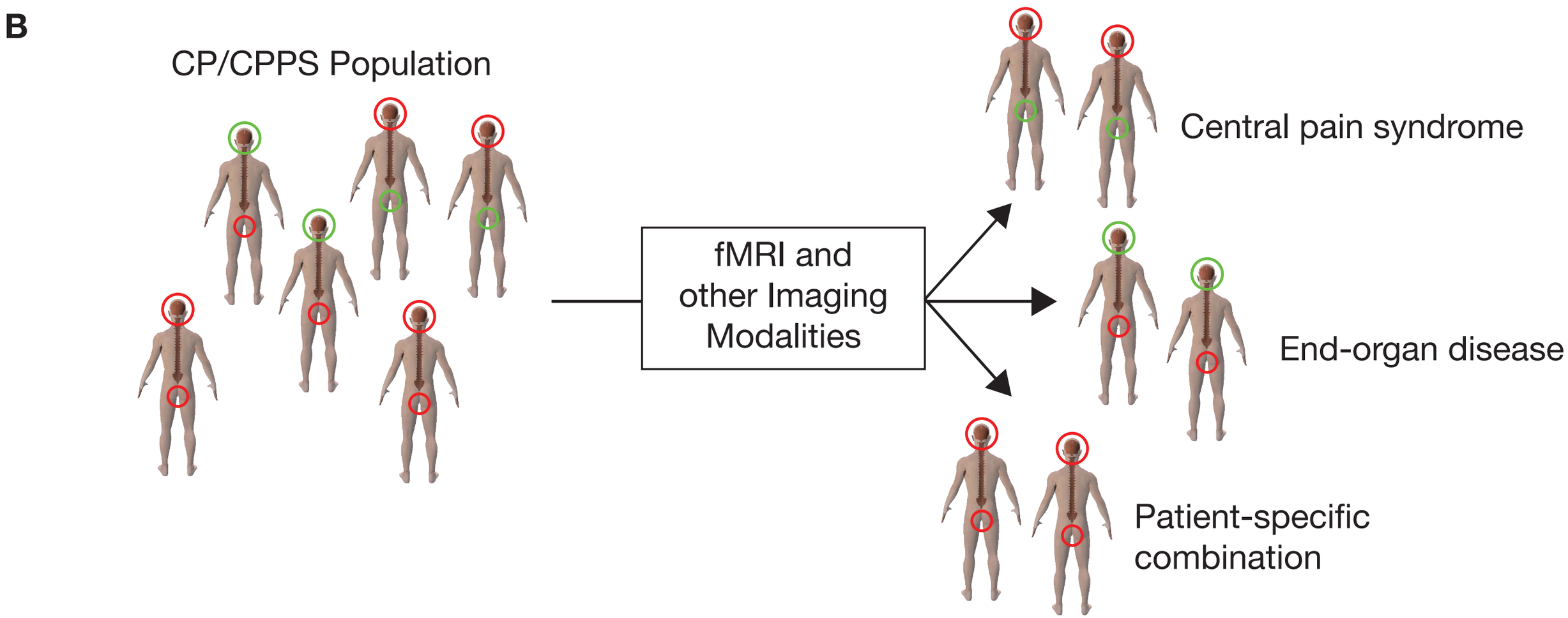
Biomechanics to Brain Pain

Central question in CP/CPPS research



Kutch et al., *In Review*

Potential CP/CPPS patient stratification



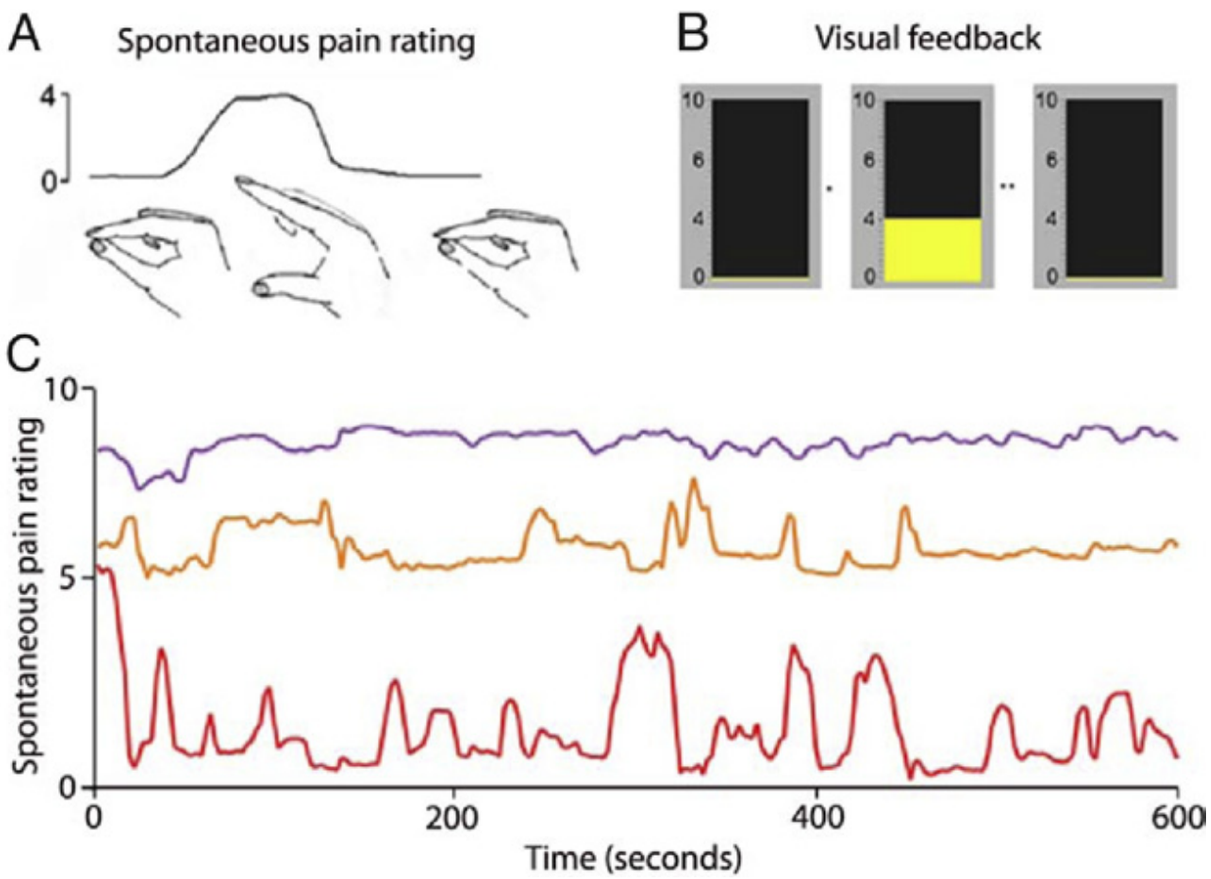
Kutch et al., *In Review*

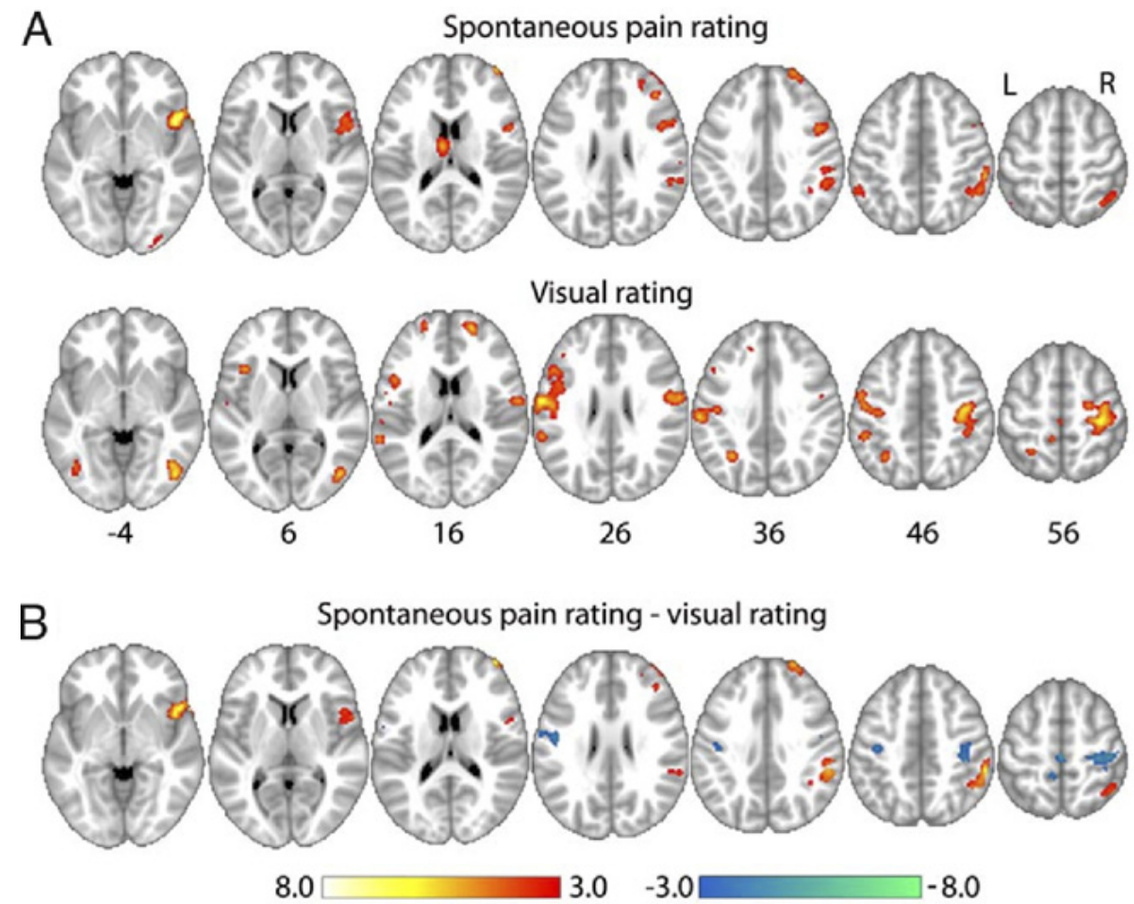
PT targets soft tissues, nerves, and muscles, including neuromuscular education

Our fMRI/PT approach

Our fMRI/PT approach

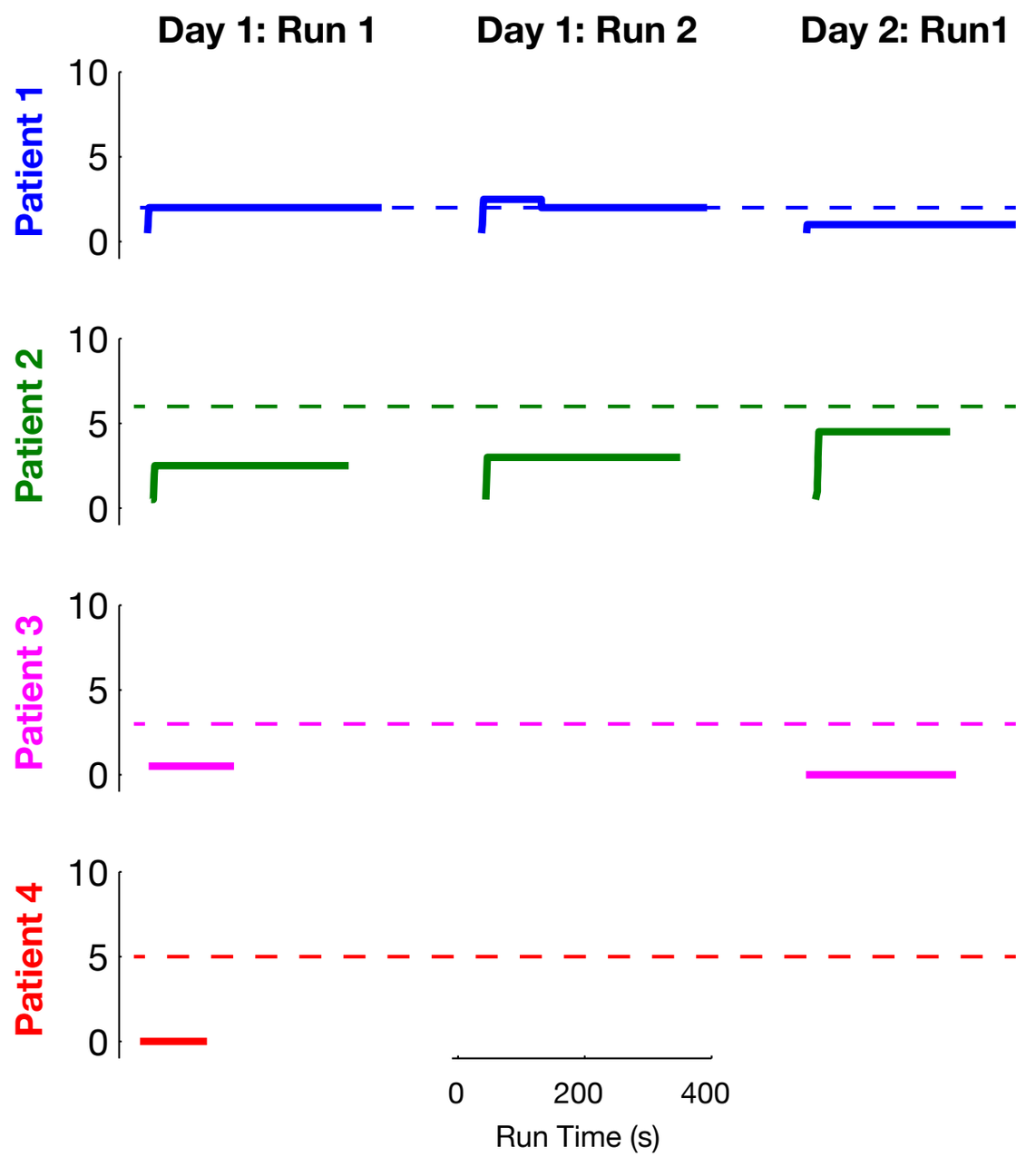
Biomechanics to Brain Pain





Farmer et al., 2011

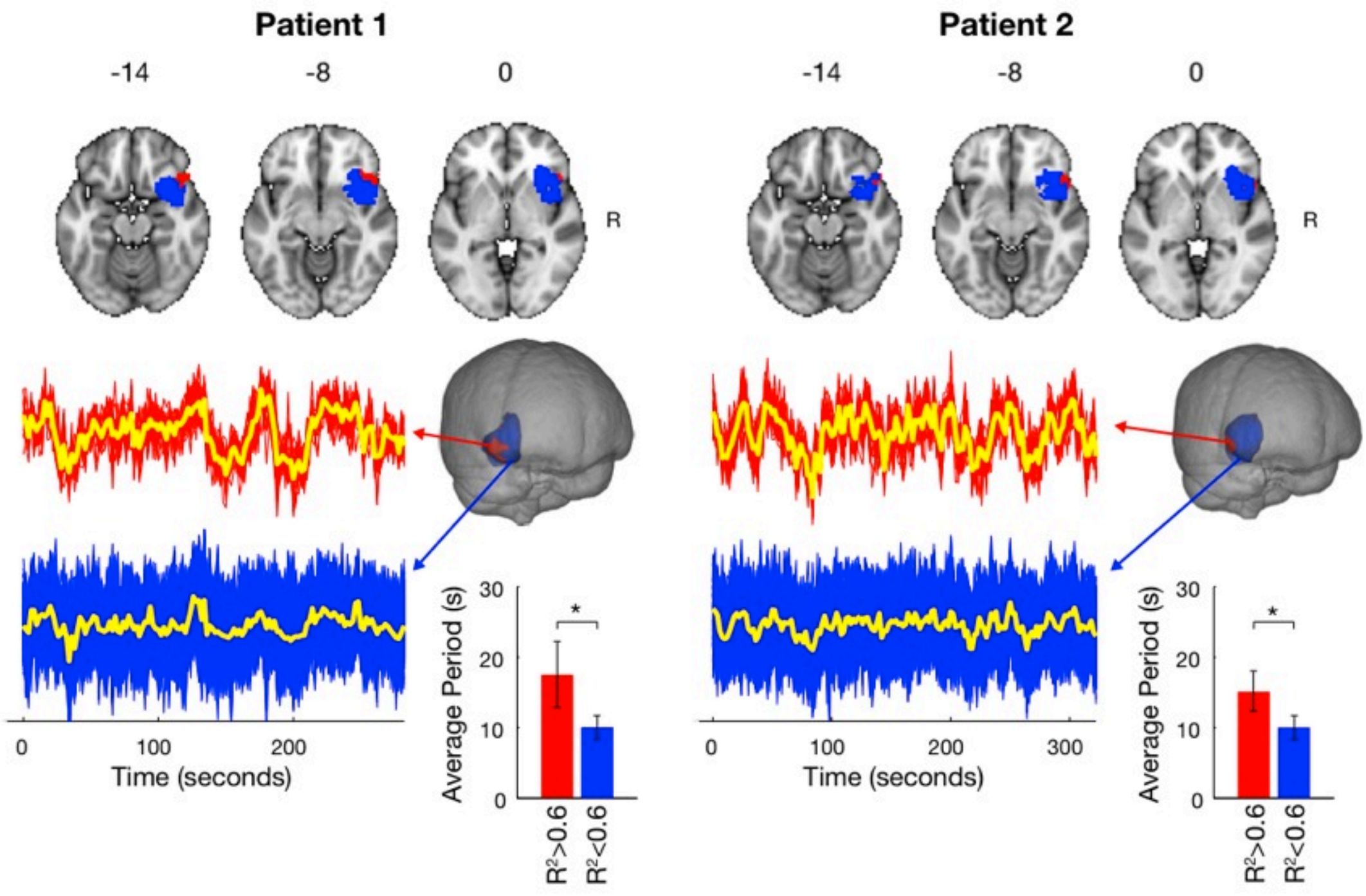
No fluctuations in conscious pain



- - - - NIH-CPSI Q4: Which number best describes your AVERAGE pain or discomfort on the days you had it, over the last week?

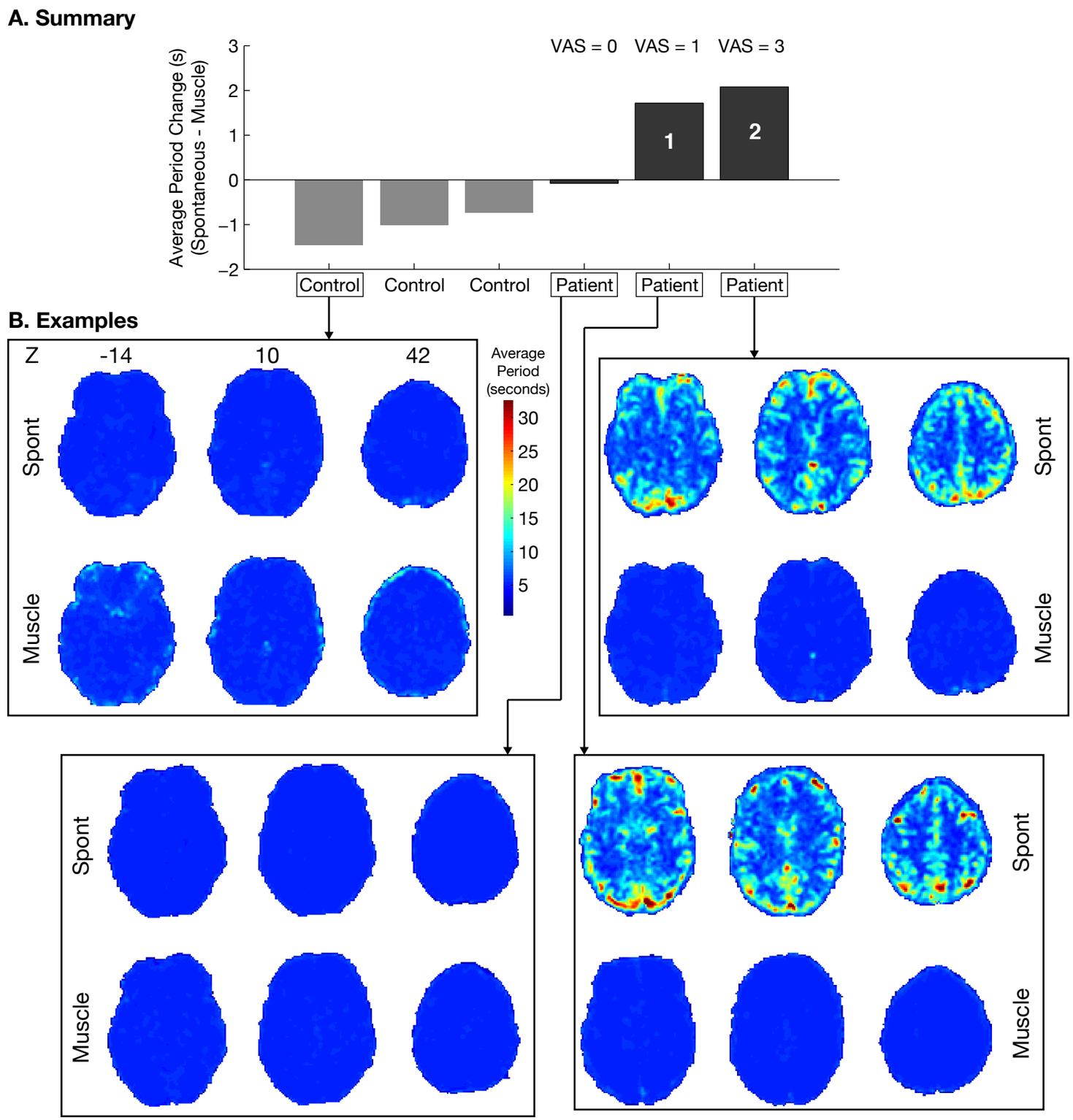
Kutch et al., *In Review*

Spontaneous low-frequency BOLD fluctuations



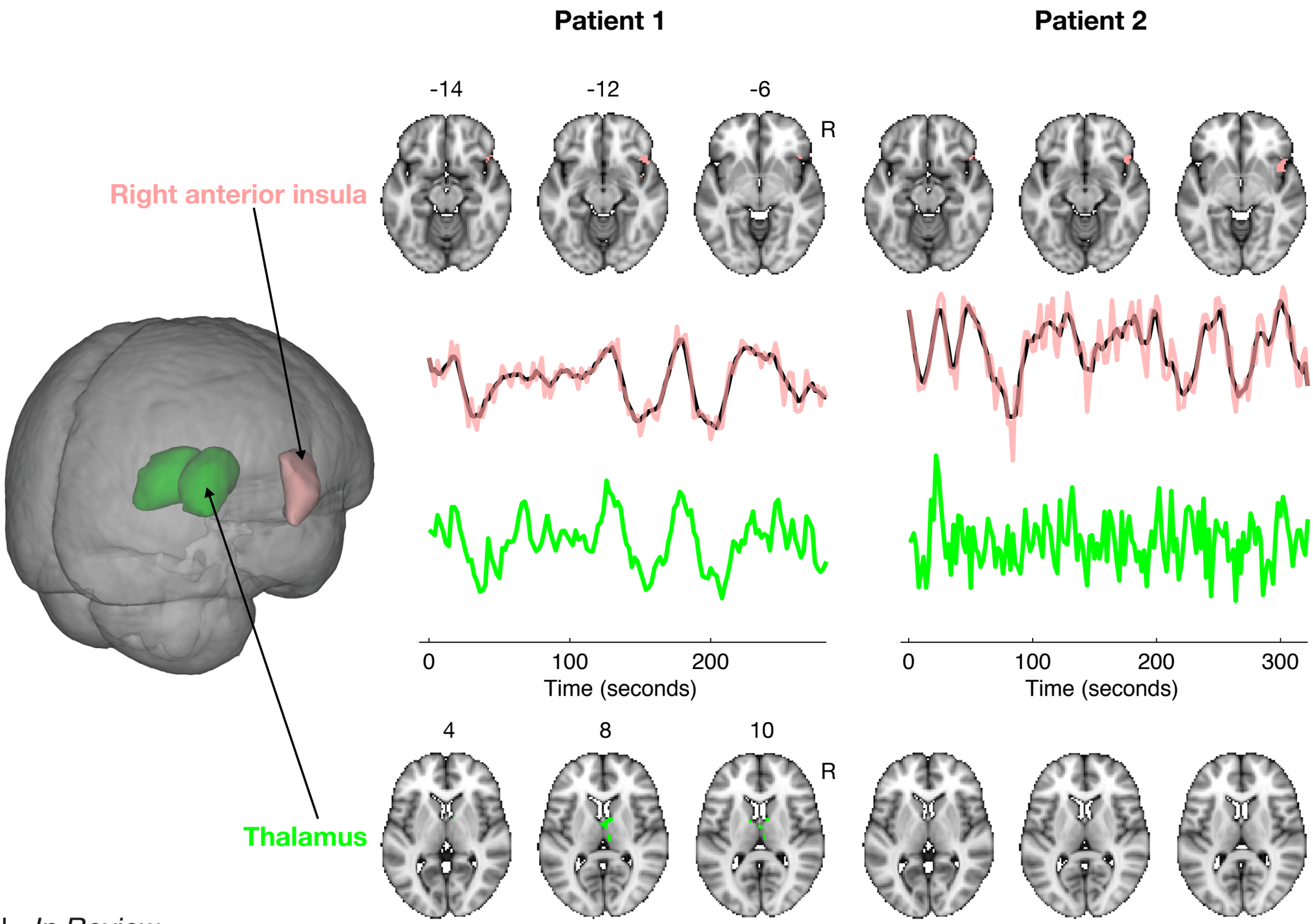
Kutch et al., *In Review*

Fluctuations are patient- and task-specific



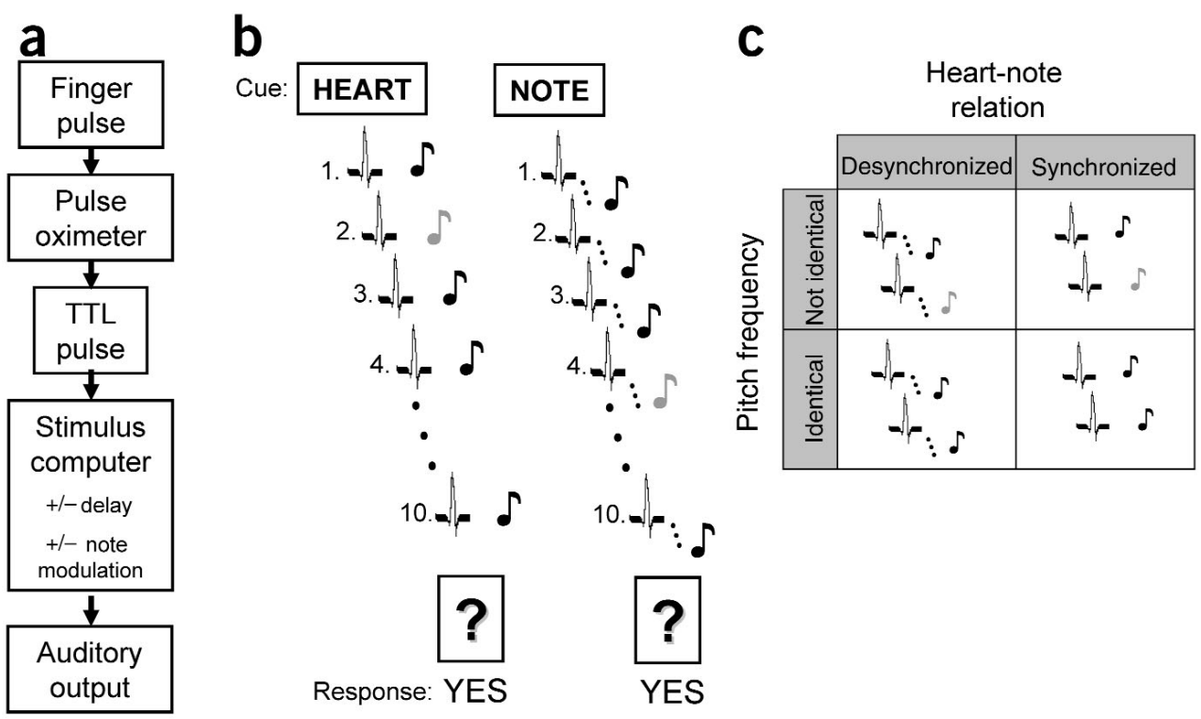
Kutch et al., *In Review*

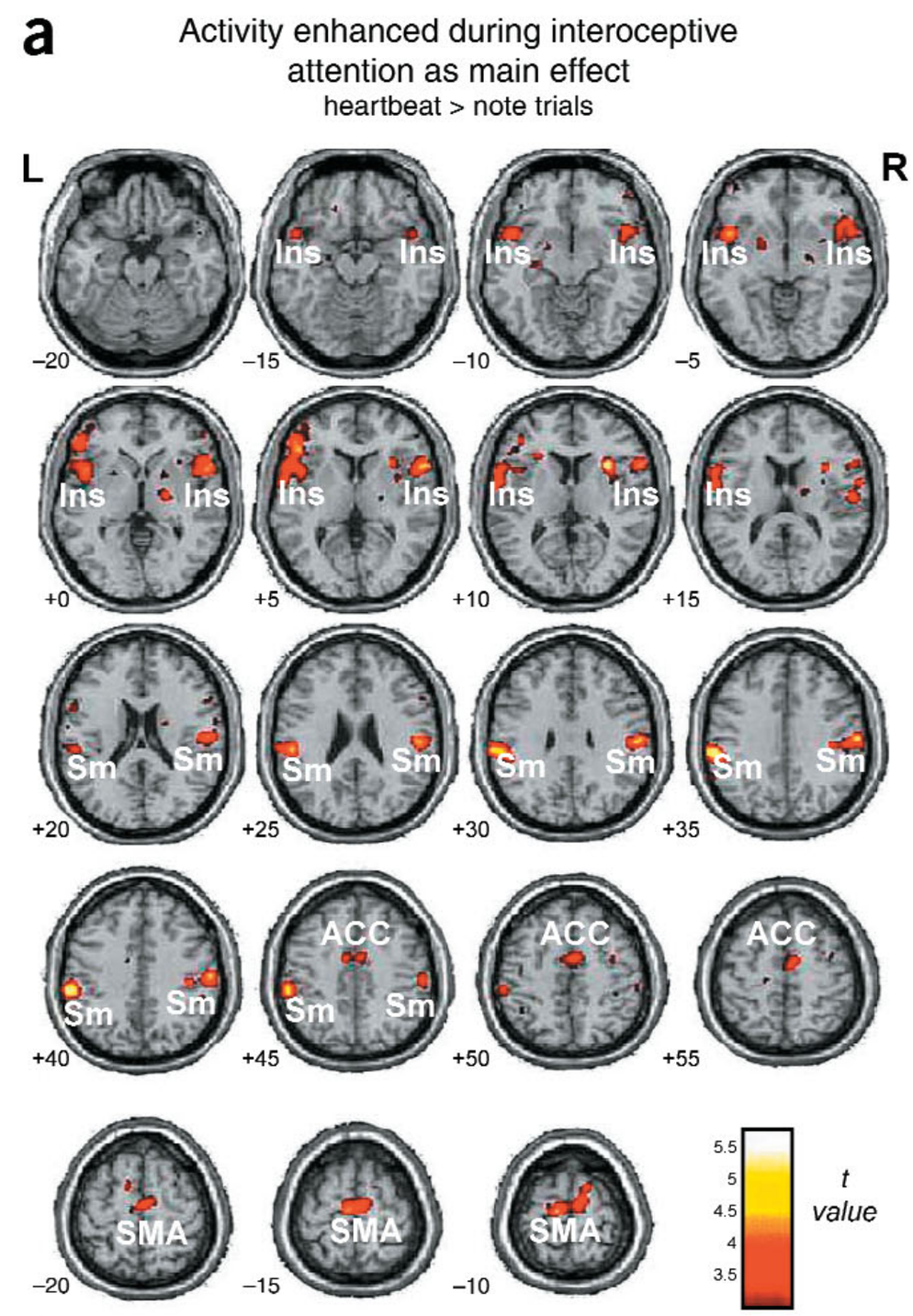
Network differences among patients



Kutch et al., *In Review*

One ignorable peripheral oscillation (heartbeat)

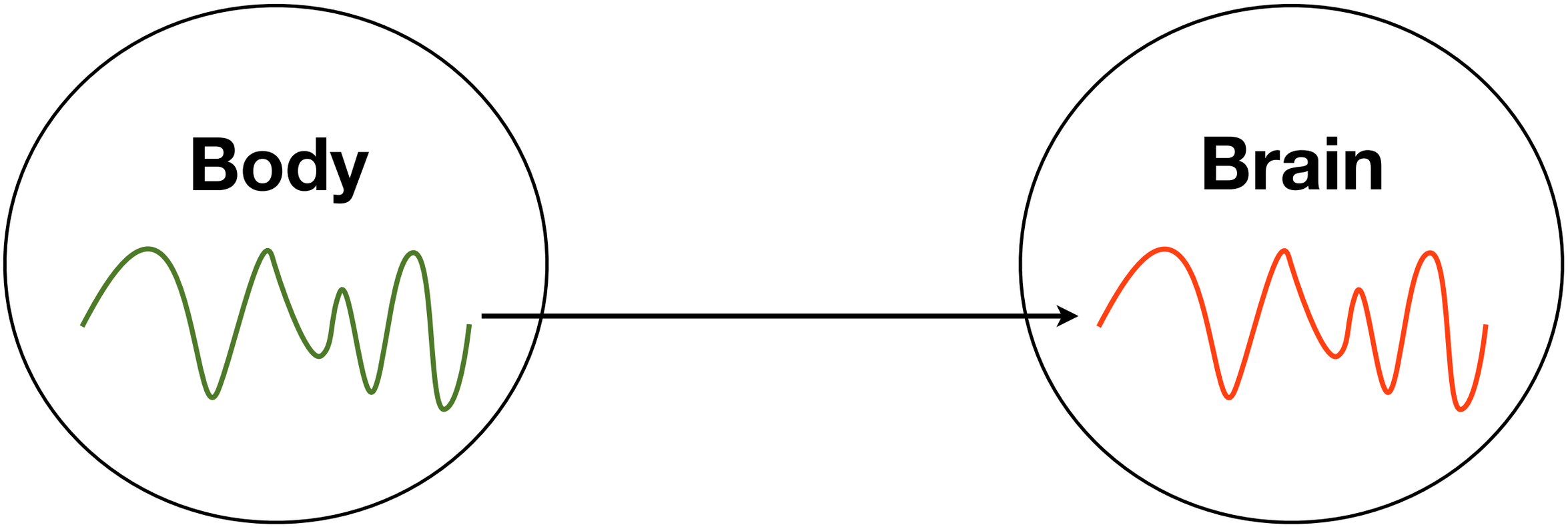




Critchley et al., 2004

Importance of neuromechanical thinking

without neuromech.: first thought is pathological brain



with neuromech.: first thought is driving peripheral oscillations

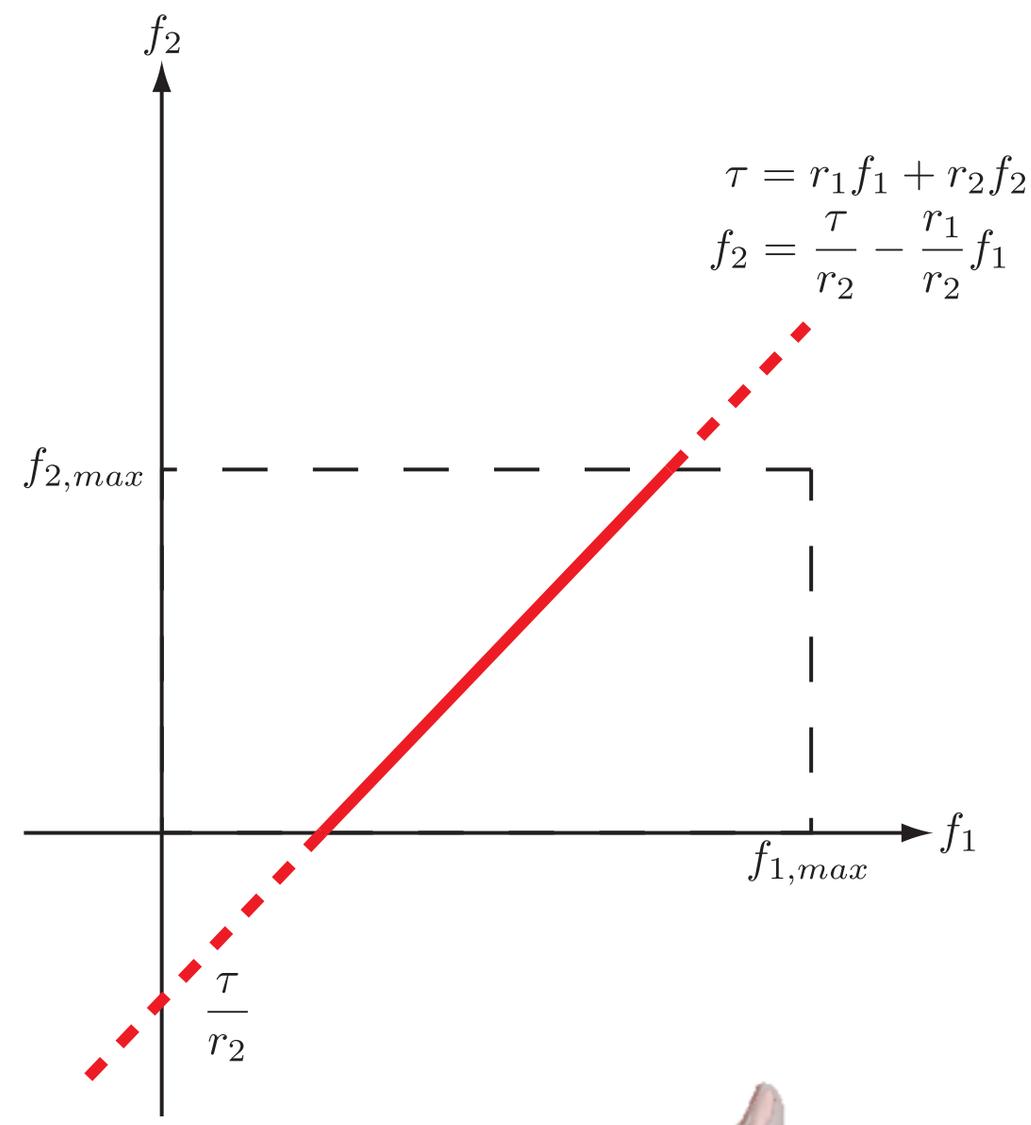
Part 1:

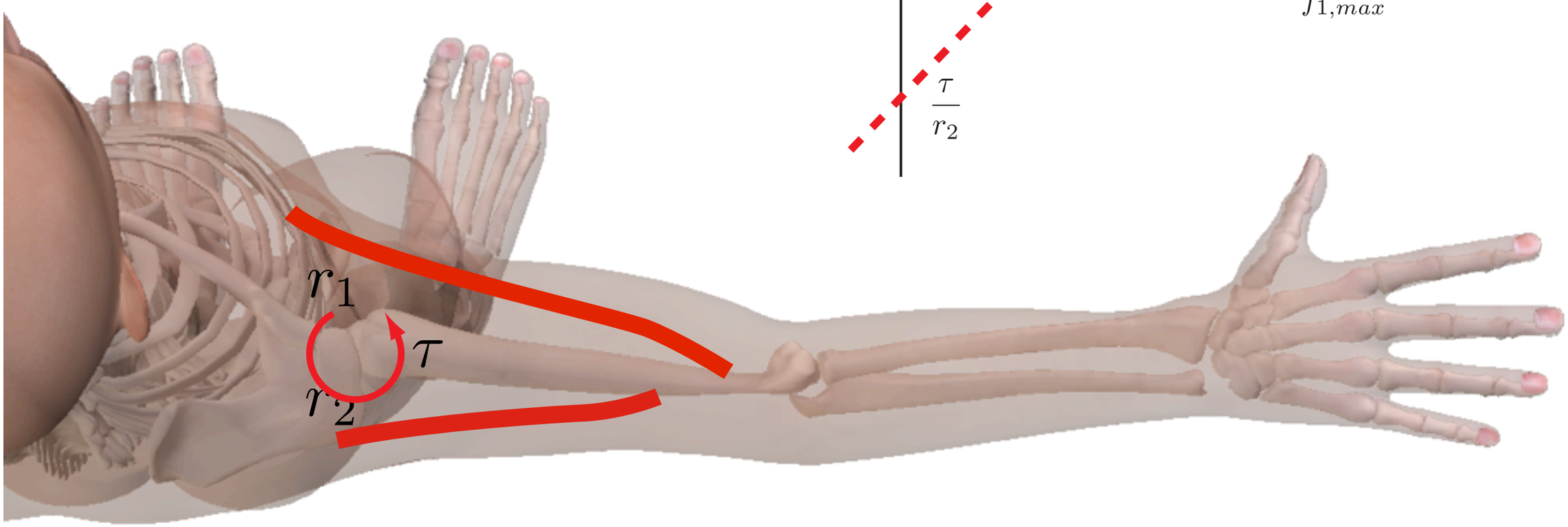
Peripheral fluctuations from muscle redundancy

Muscle redundancy

Muscle redundancy

Muscle redundancy can be viewed geometrically as the intersection of hyperplanes and hypercubes





Muscle redundancy

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www.JBiomech.com

Muscle redundancy does not imply robustness to muscle dysfunction

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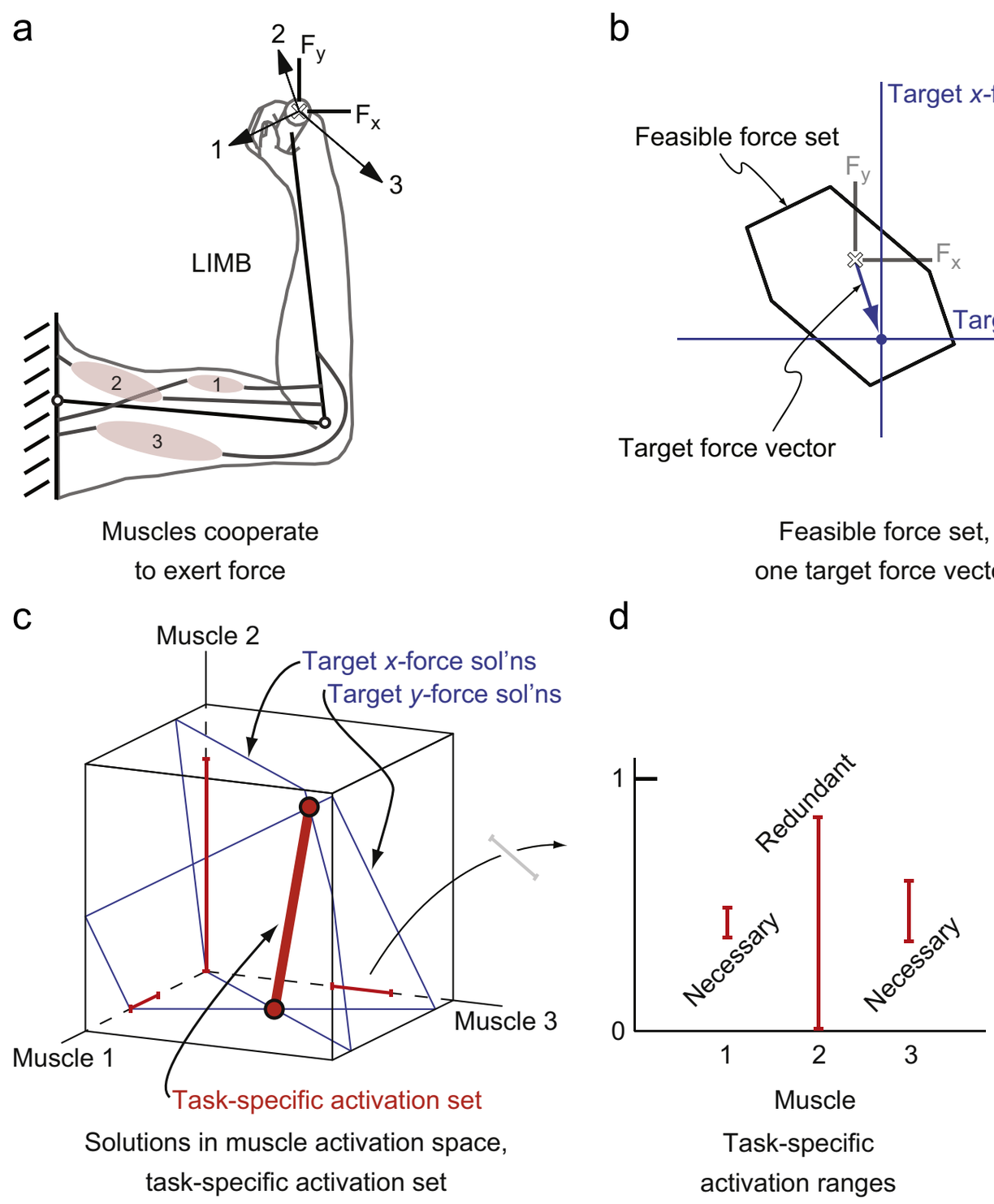
Limb biomechanics

ABSTRACT

It is well-known that muscle redundancy grants the CNS numerous options to perform a task. Does muscle redundancy, however, allow sufficient robustness to compensate for loss or dysfunction of even a single muscle? Are all muscles equally redundant? We combined experimental and computational approaches to establish the limits of motor robustness for static force production. In computer-controlled cadaveric index fingers, we find that only a small subset ($<5\%$) of feasible forces is robust to loss of any one muscle. Importantly, the loss of certain muscles compromises force production significantly more than others. Further computational modeling of a multi-joint, multi-muscle leg demonstrates that this severe lack of robustness generalizes to whole limbs. These results provide a biomechanical basis to begin to explain why redundant motor systems can be vulnerable to even mild neuromuscular pathology.

Kutch & Valero-Cuevas, 2011

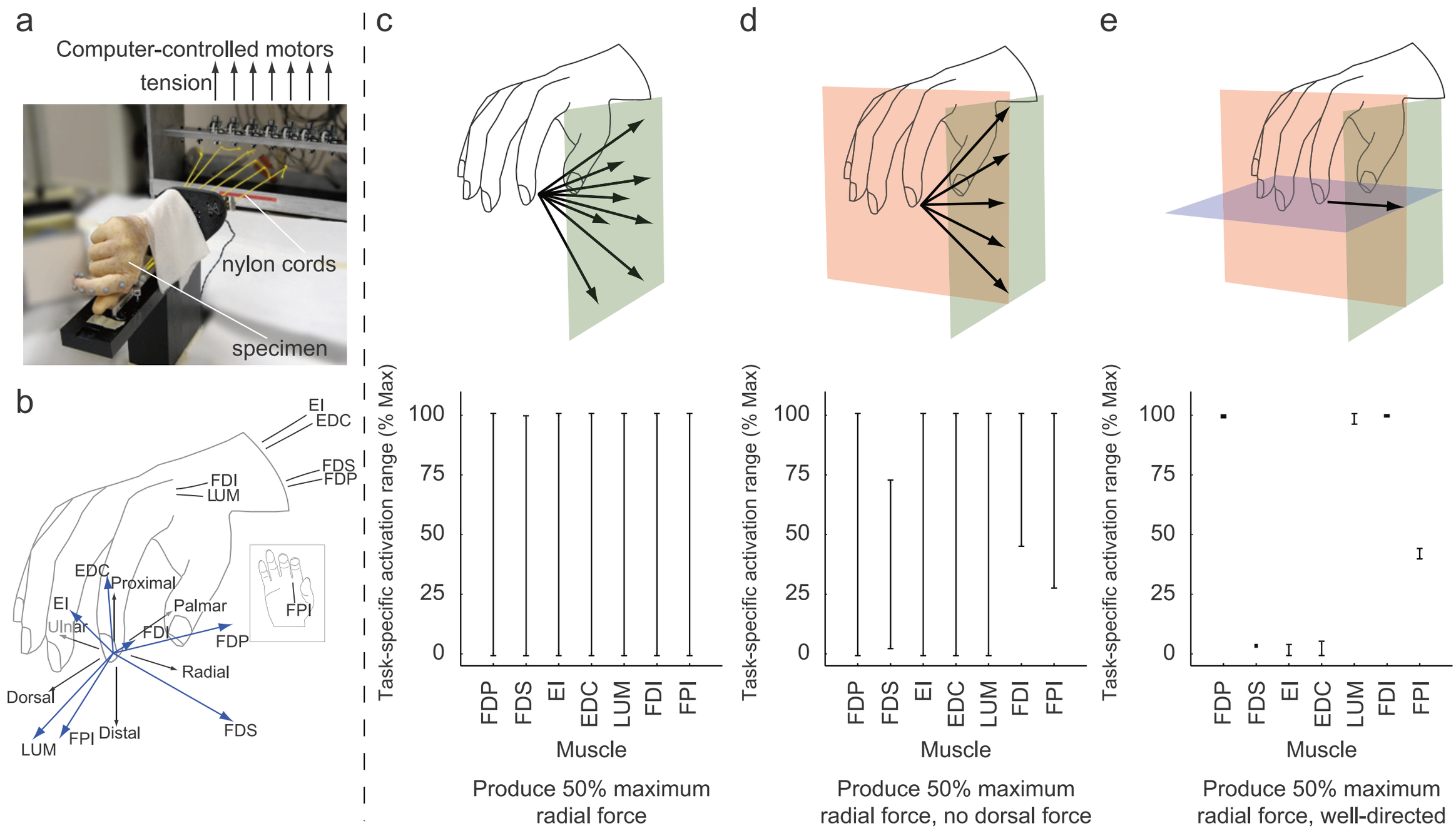
Geometric view of muscle redundancy generalizes.



Kutch & Valero-Cuevas, 2011

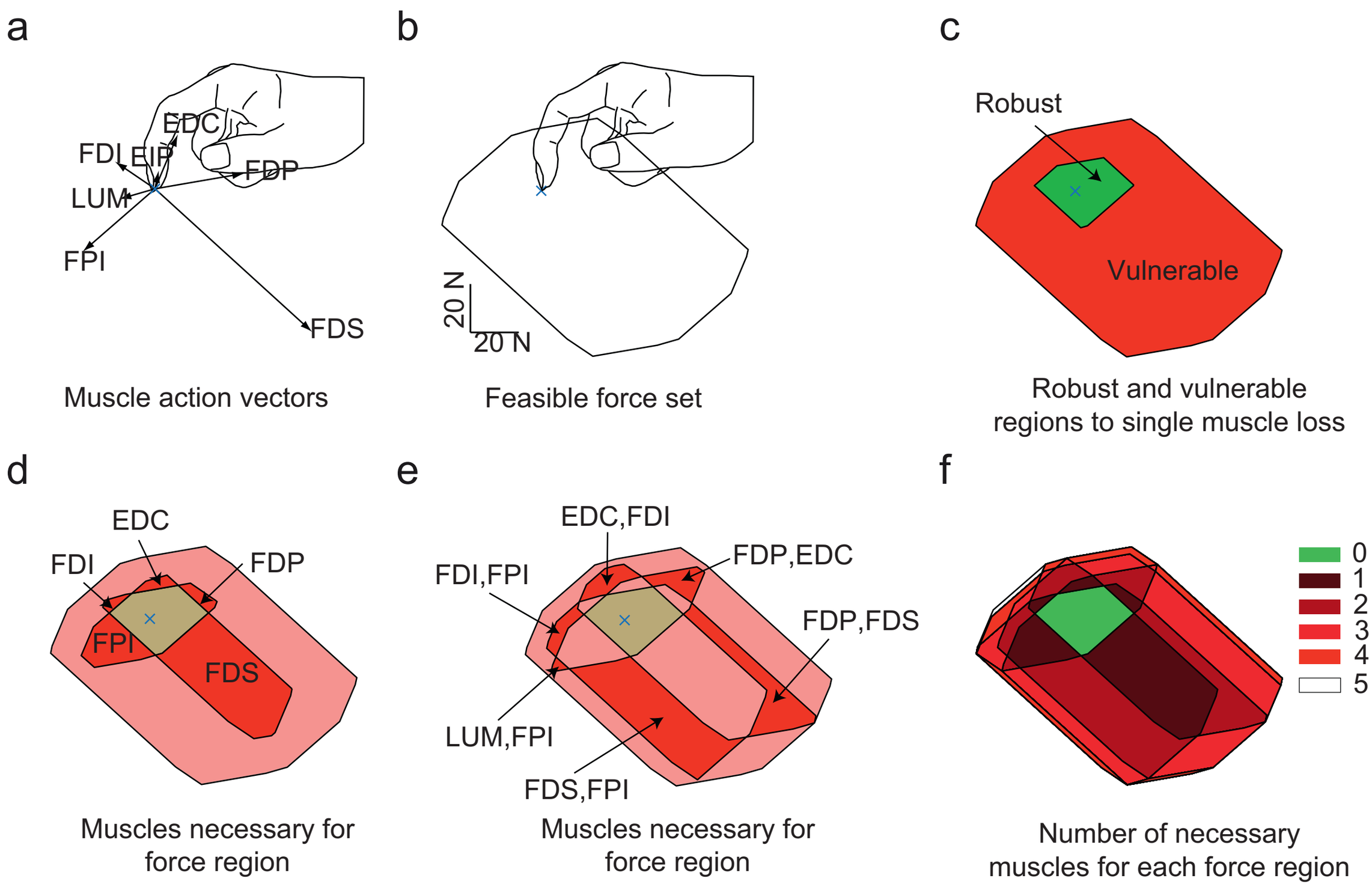
Muscle redundancy

Predictions can be made from cadaveric data.



Kutch & Valero-Cuevas, 2011

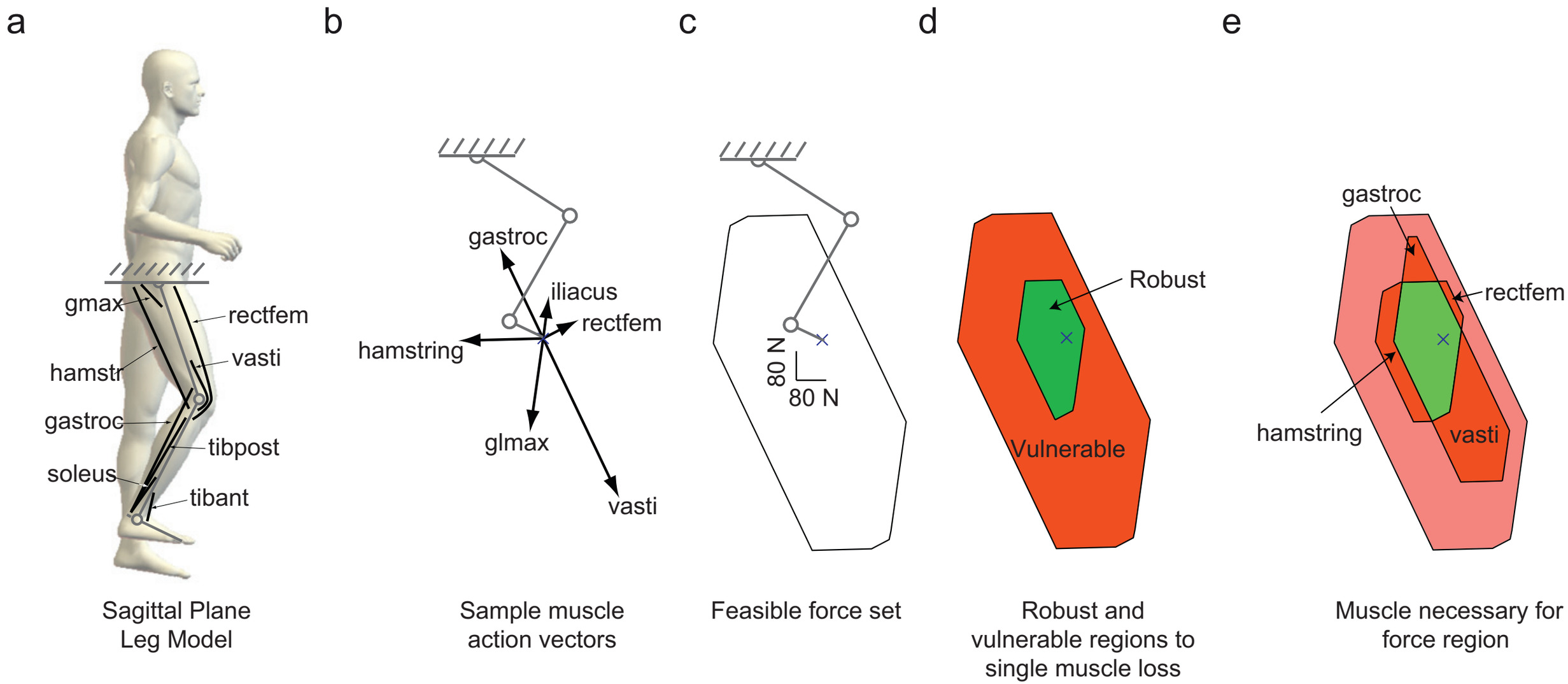
Robust regions - an one muscle can turn off.



Kutch & Valero-Cuevas, 2011

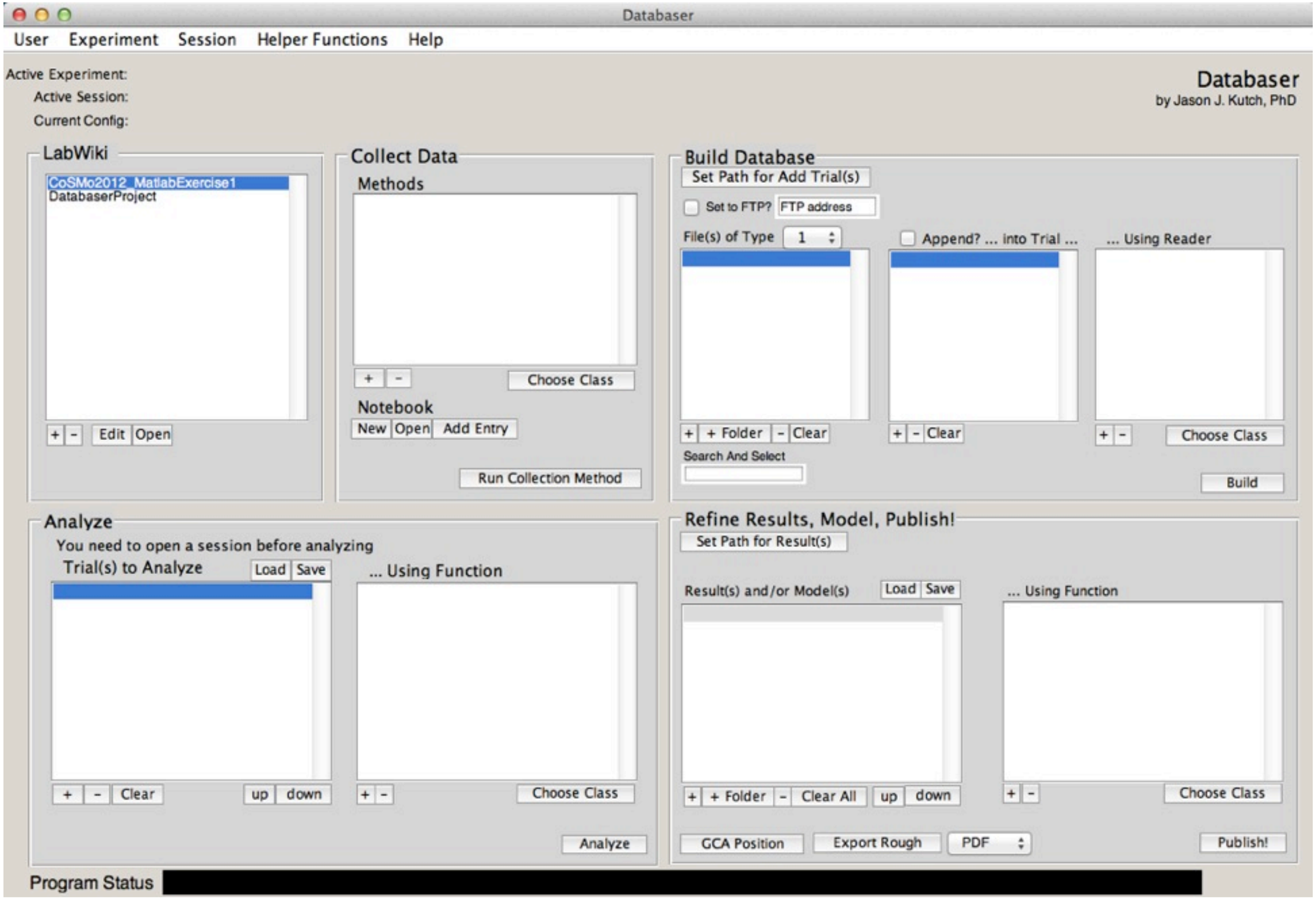
Muscle redundancy

Predictions can also be made from biomechanical models.



Kutch & Valero-Cuevas, 2011

MATLAB


Databaser
User
Experiment
Session
Helper Functions
Help
Active Experiment:
Active Session:
Current Config:
Databaser
by Jason J. Kutch, PhD
LabWiki
CoSMo2012_MatlabExercise1
DatabaserProject
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Run Collection Method
Build Database
Set Path for Add Trial(s)
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-
Choose Class
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Result(s) and/or Model(s)
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Save
... Using Function
+
+ Folder
-
Clear All
up
down
+
-
Choose Class
GCA Position
Export Rough
PDF
Publish!
Program Status

Computational Geometry

Monte-Carlo Methods

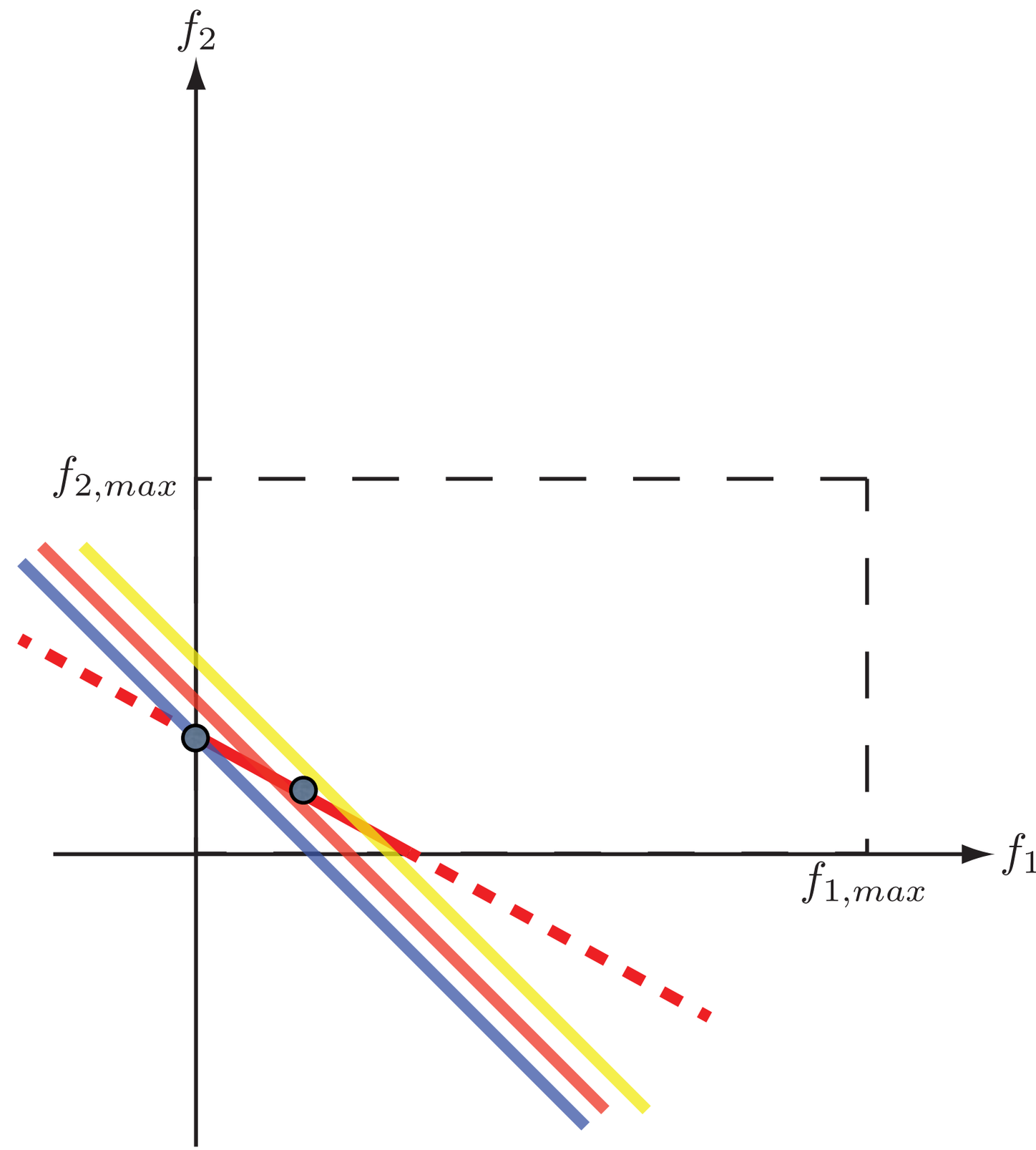
Optimization focuses on a solution

Example 1: Linear cost function

$$J(f) = \sum_{i=1}^{n} f_i$$

$$\min_f f_1 + f_2$$
$$\text{such that } Rf = \tau_d$$

linprog in MATLAB



Muscle redundancy

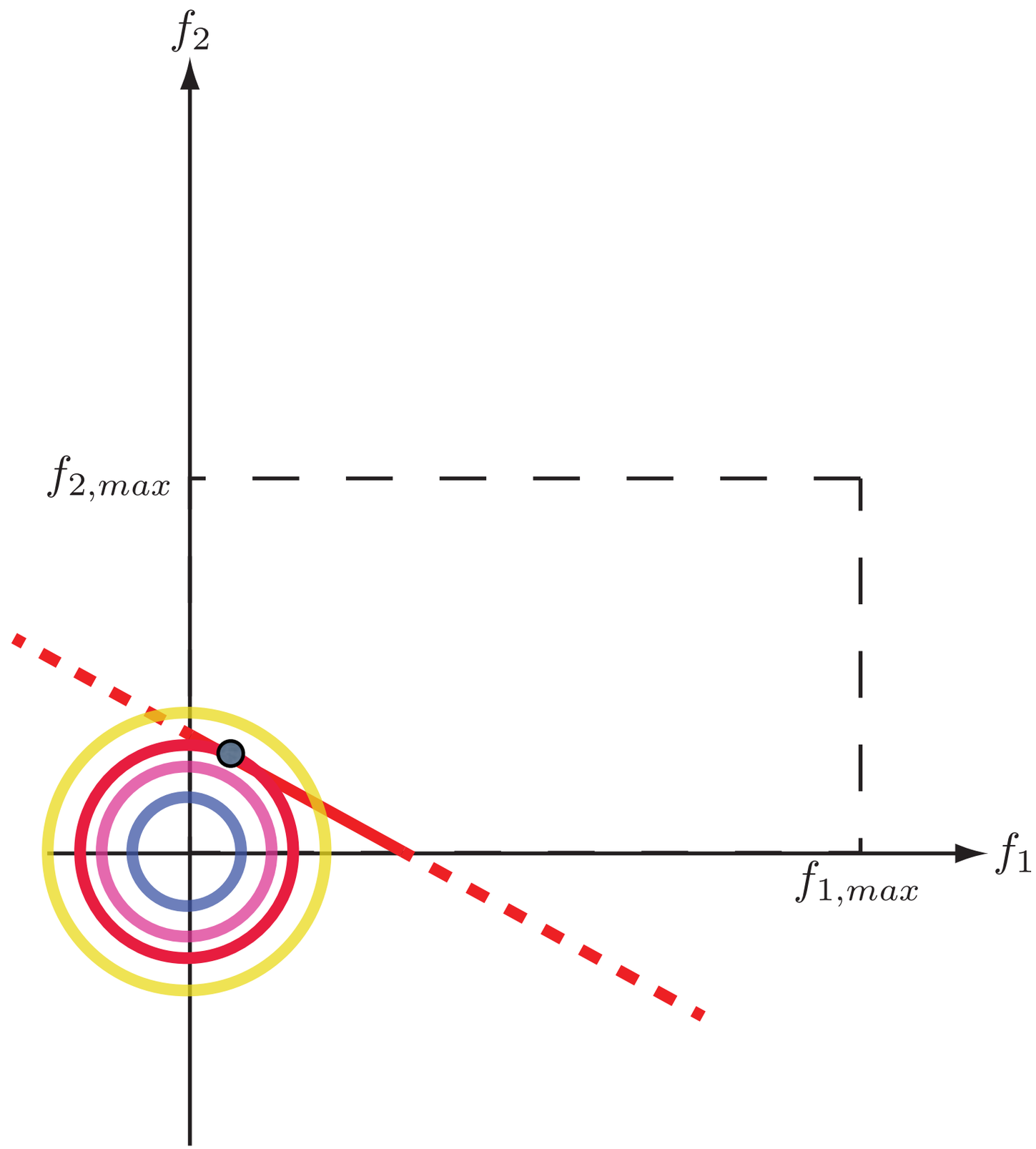
Example 2: Quadratic cost function

$$J(f) = \sum_{i=1}^{n} f_i^2$$

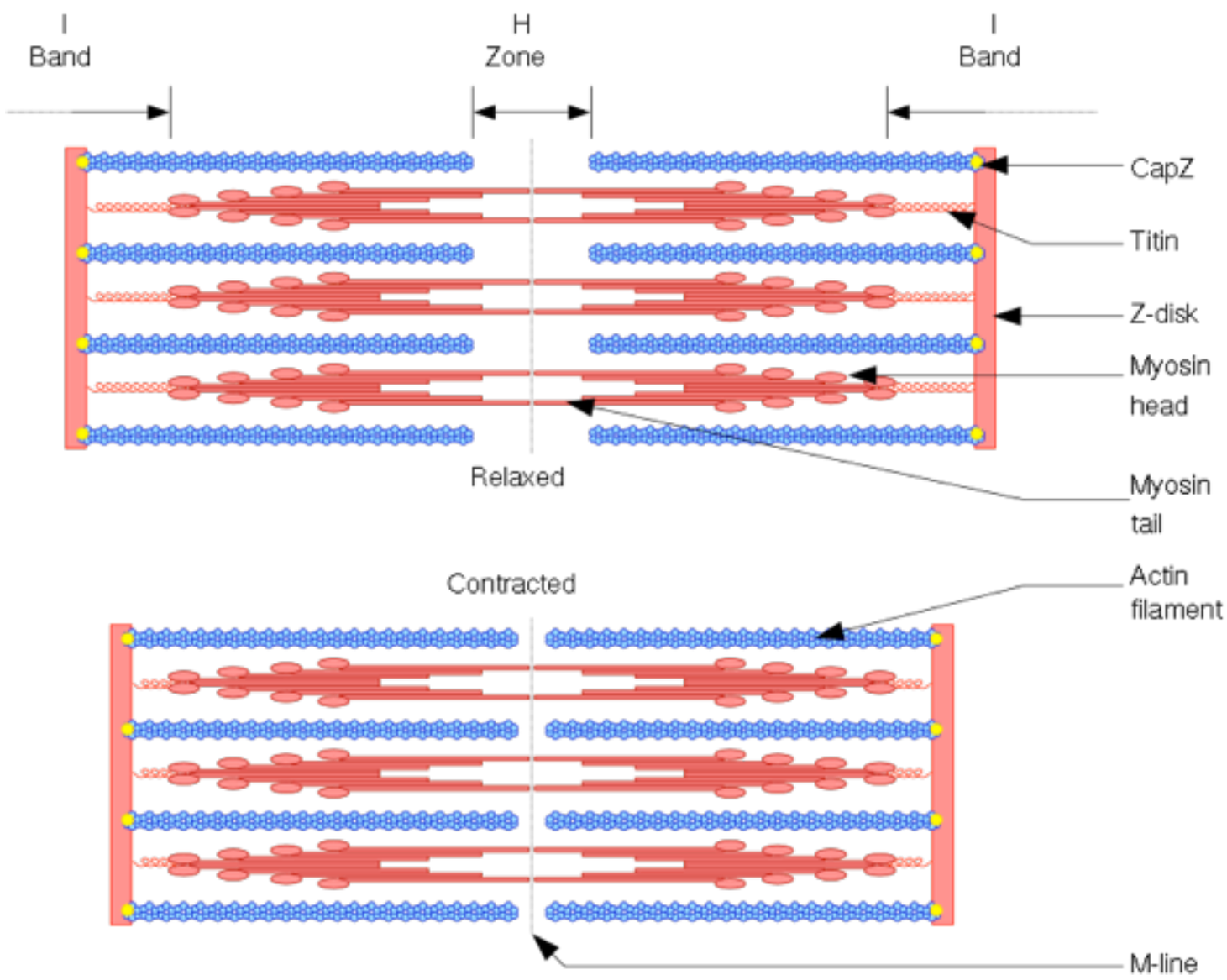
$$\min_f f_1^2 + f_2^2$$

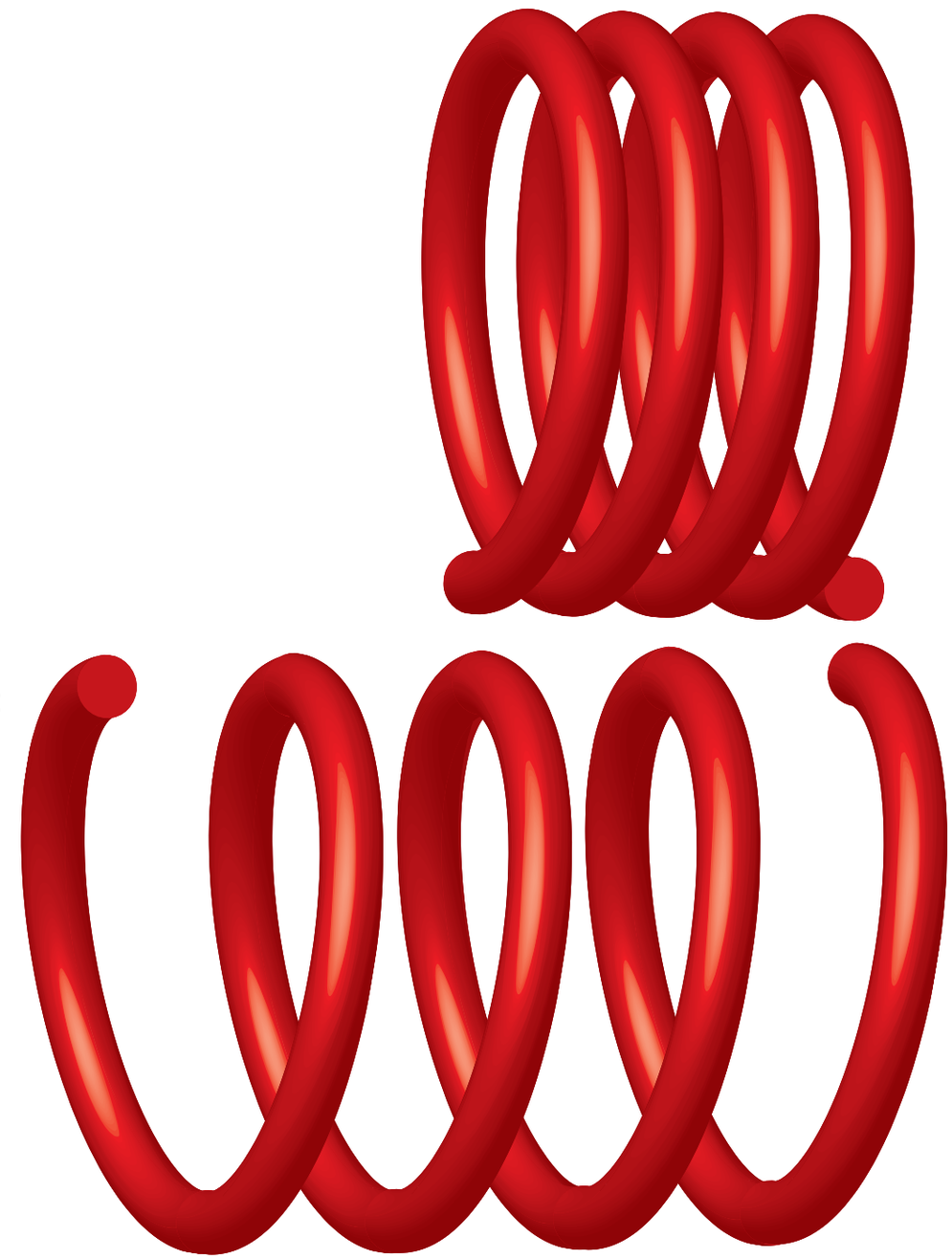
$$\text{such that } Rf = \tau_d$$

quadprog in MATLAB

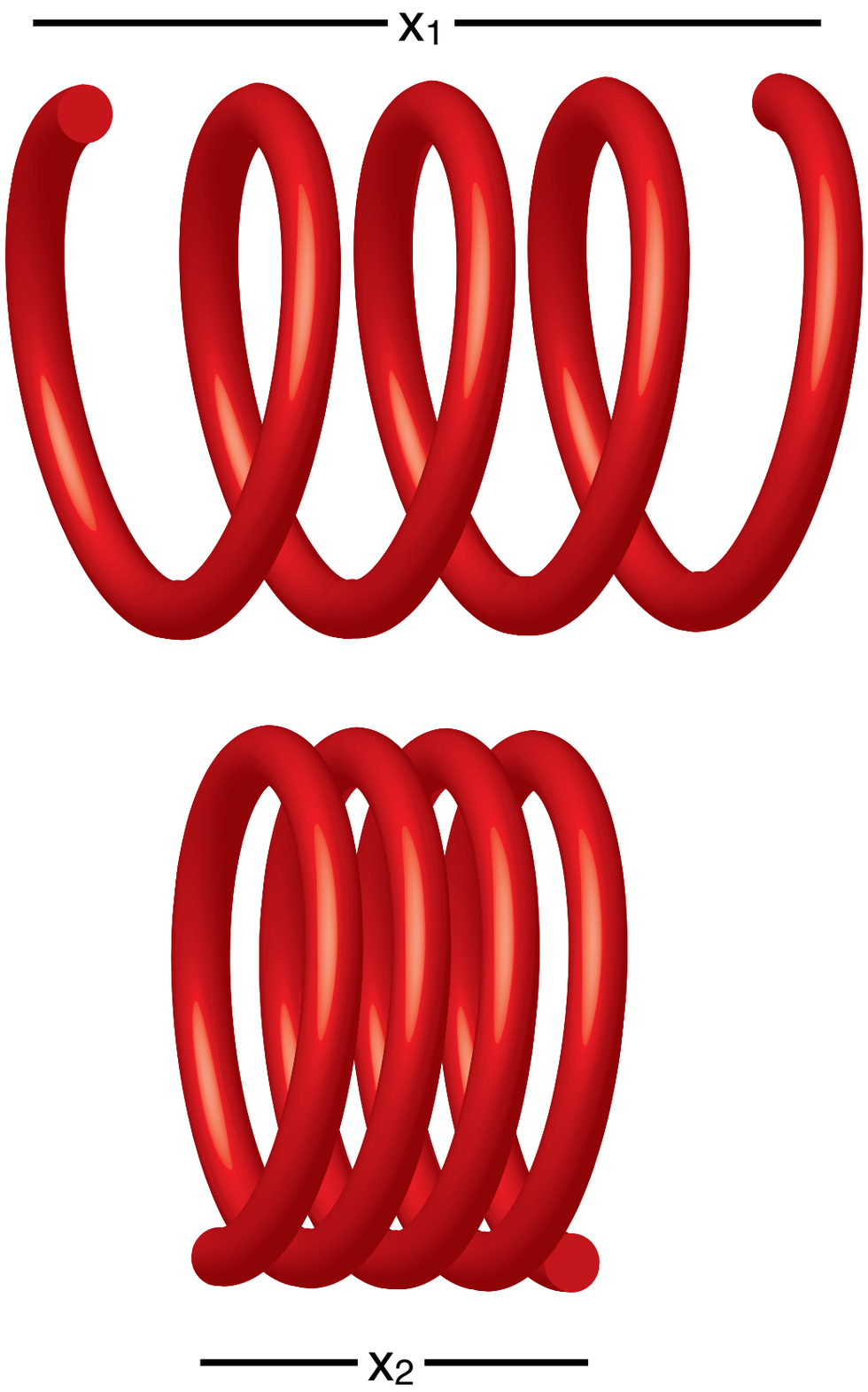


Muscle redundancy





Muscle redundancy



$$\Delta x = x_2 - x_1$$

$$F = k\Delta x$$

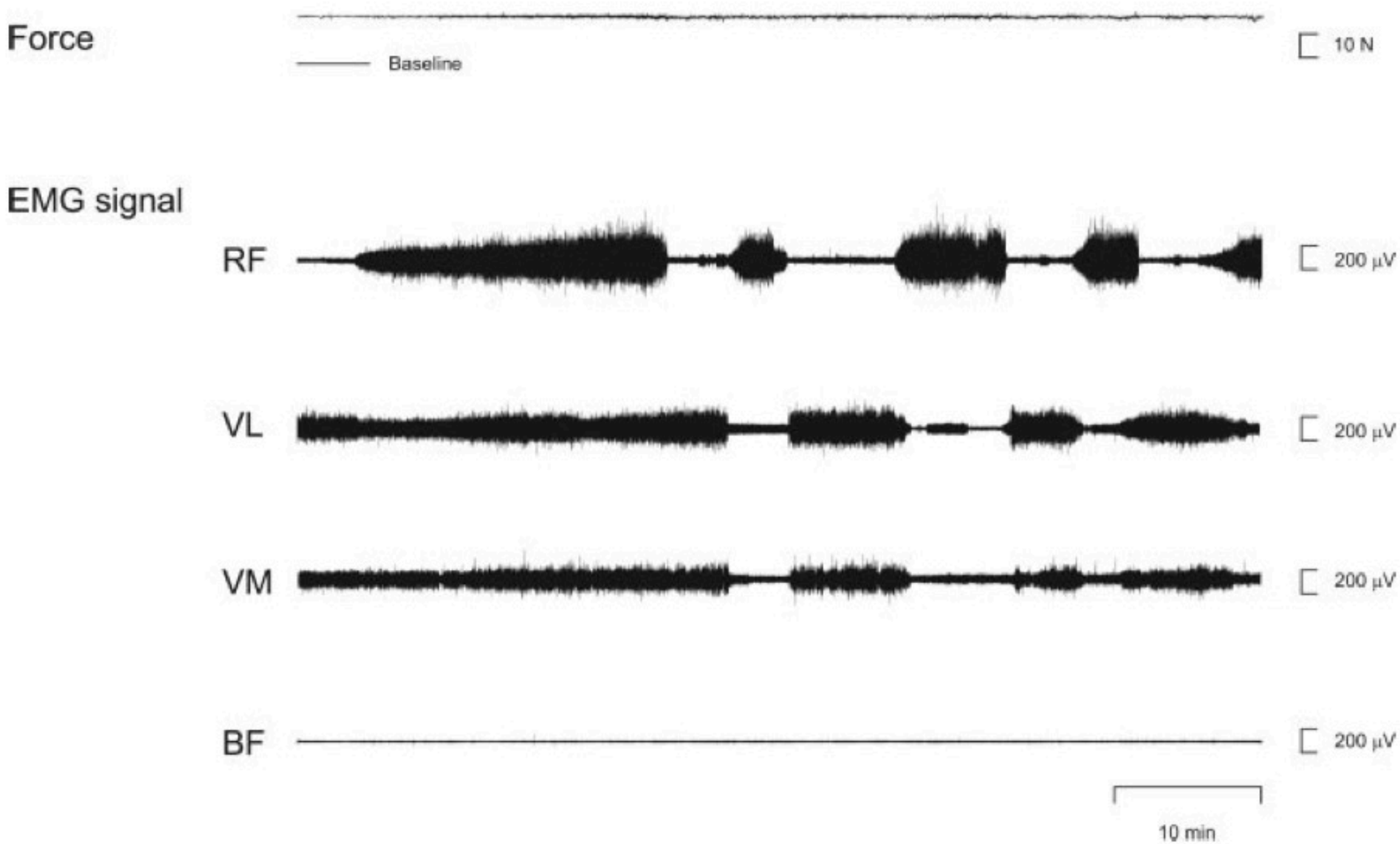
$$E = \frac{1}{2}k(\Delta x)^2$$

$$E = \frac{1}{2}k\left(\frac{F}{k}\right)^2$$

$$E = \frac{1}{2k}F^2$$

Muscle coordination prediction by Optimization

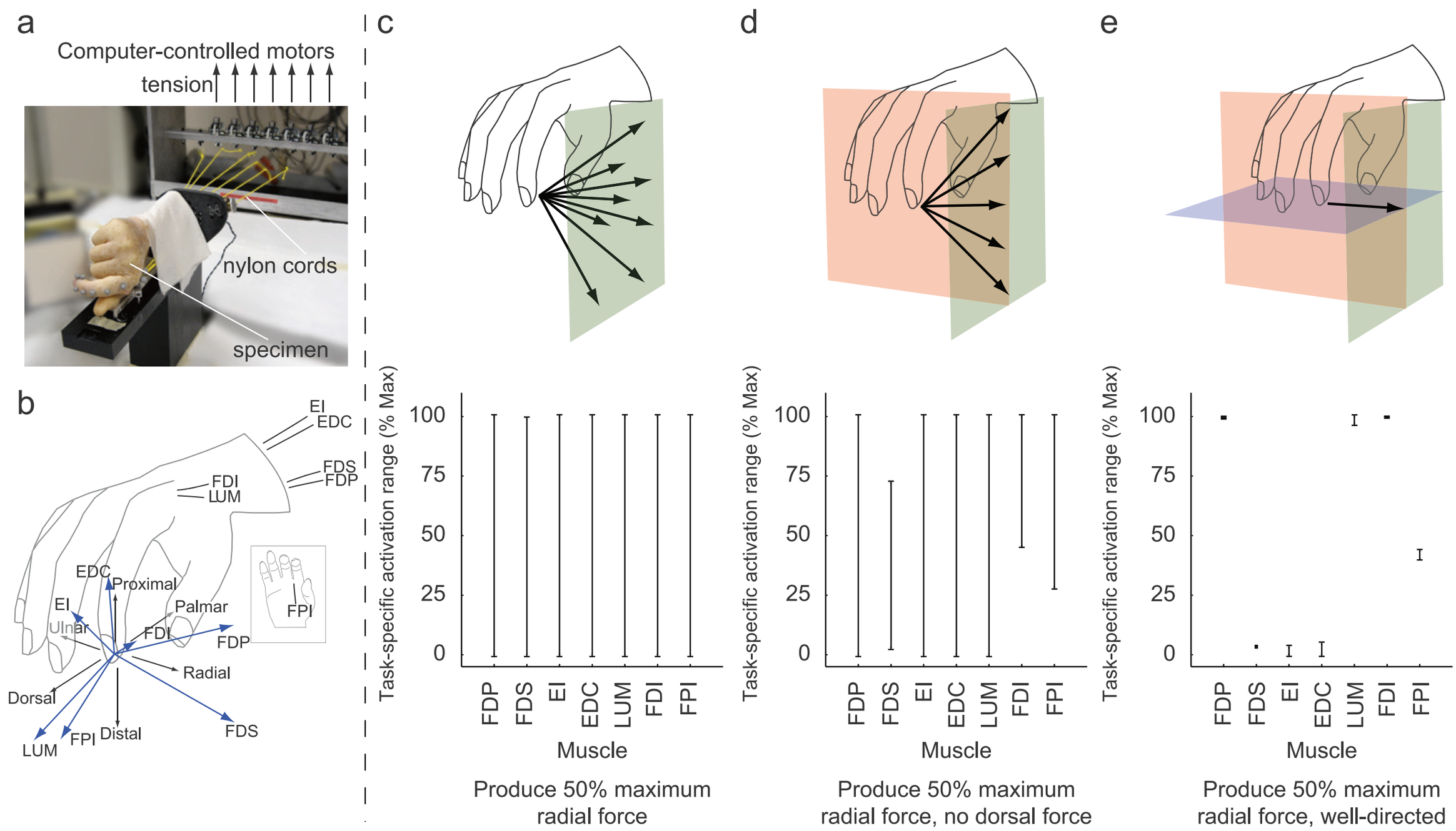
Muscle redundancy



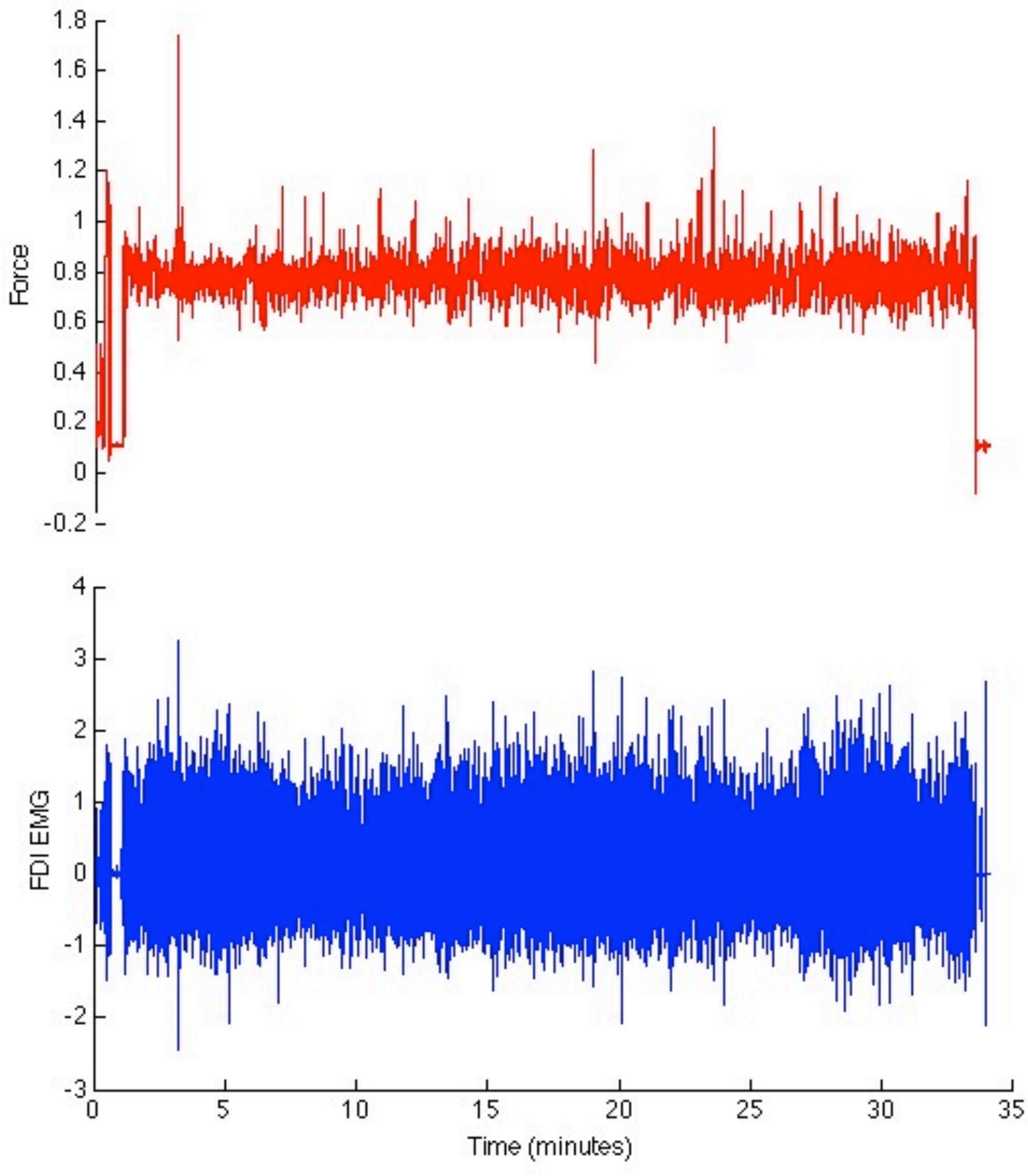
Kouzaki and Shinohara, 2006

Prediction of muscle switching by dynamic re-optimization

Not all muscles will switch during sustained contraction



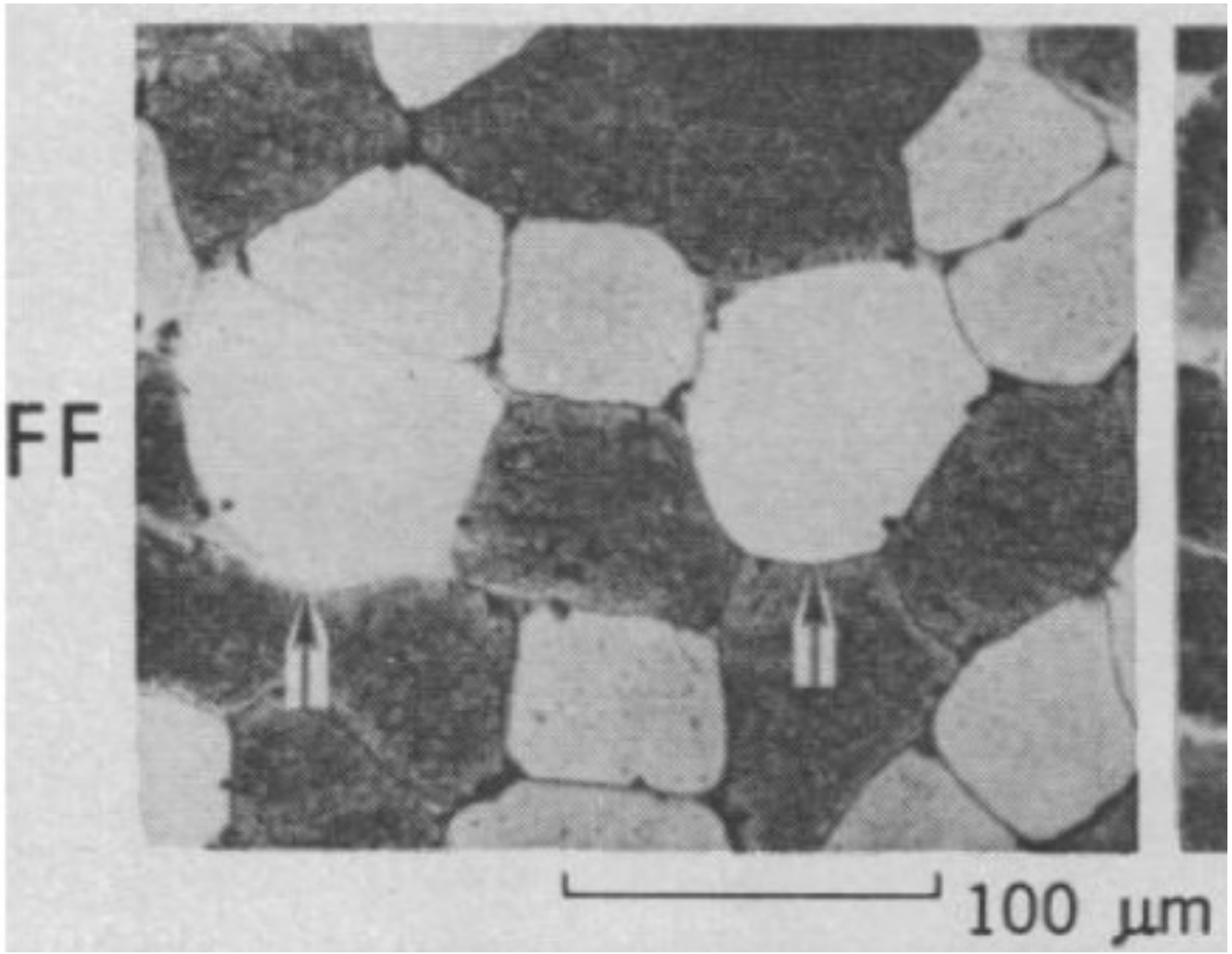
Muscle redundancy



Part 2:
Peripheral fluctuations from motor unit redundancy

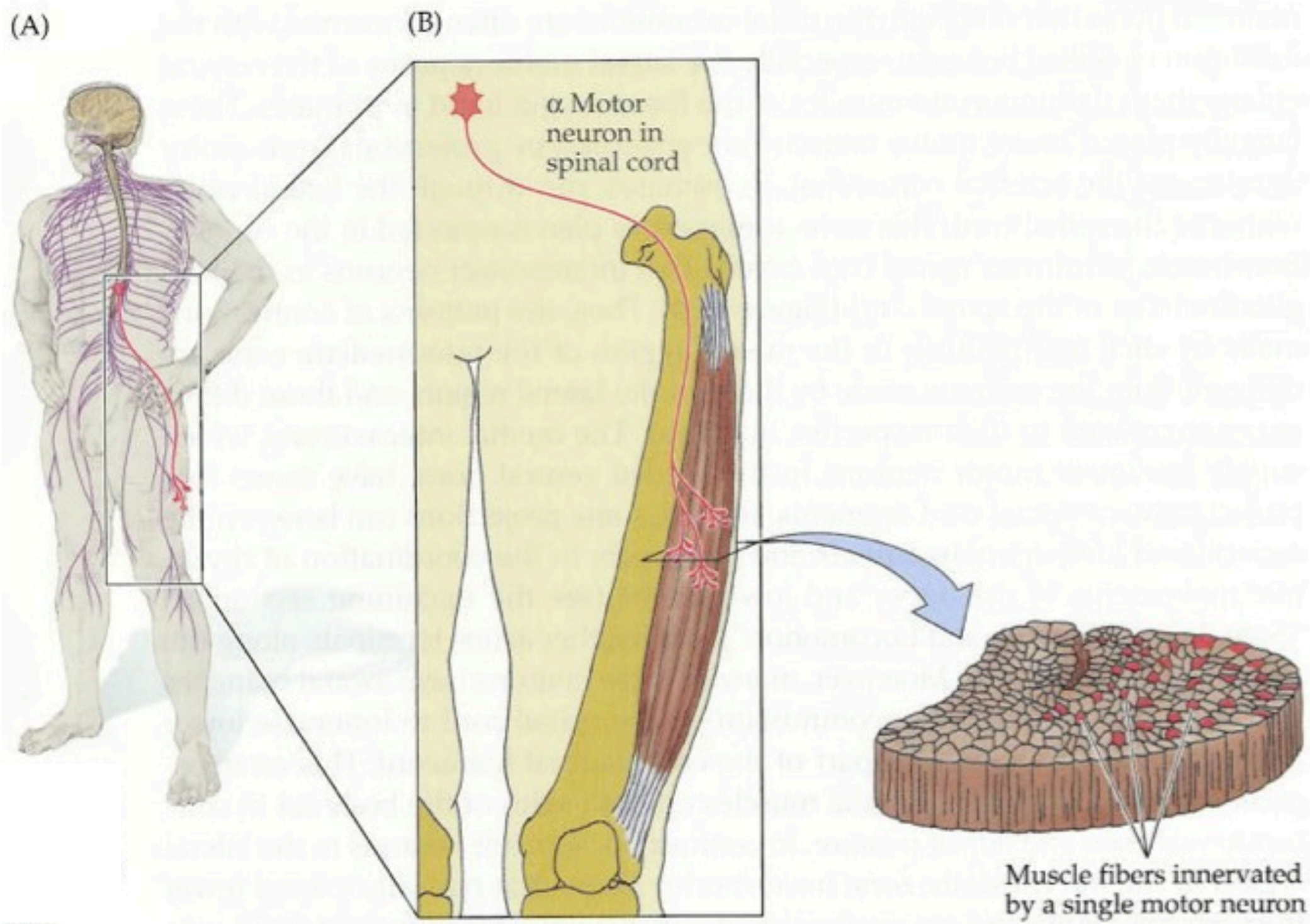
Motor unit redundancy

Muscle fiber = muscle cell.
Motor unit = group of muscle fibers.



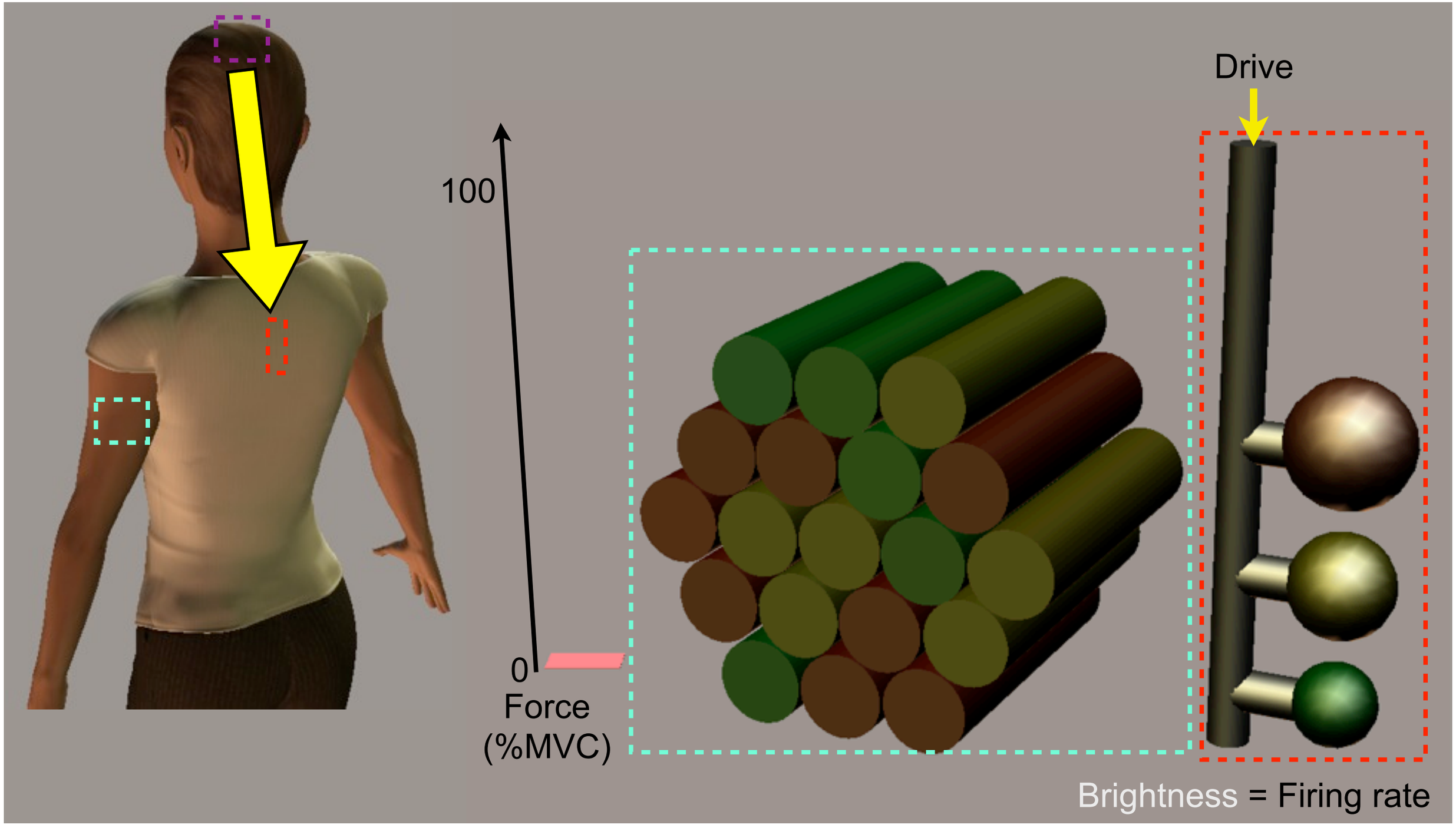
Burke et al. 1971

Motor unit redundancy



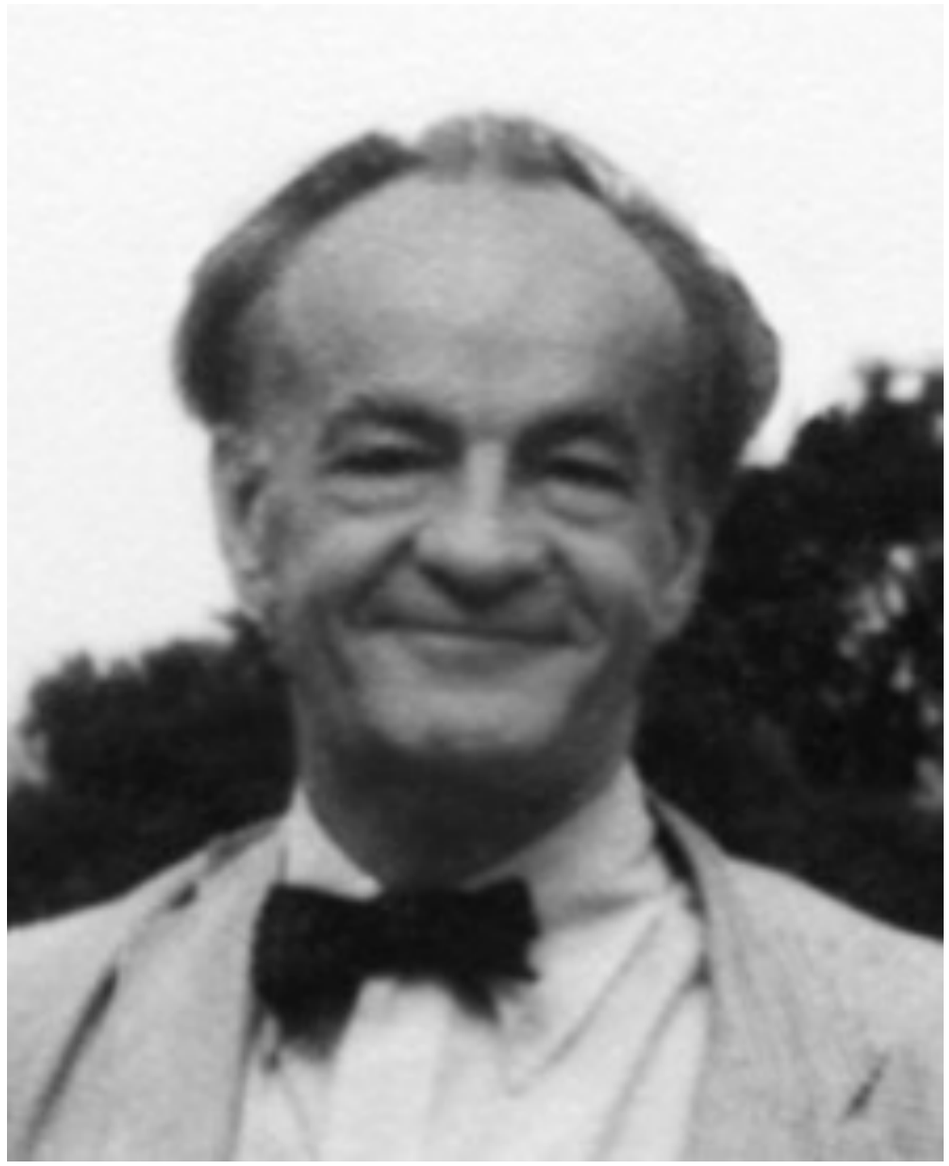
Purves et al.

Motor units are sequentially activated

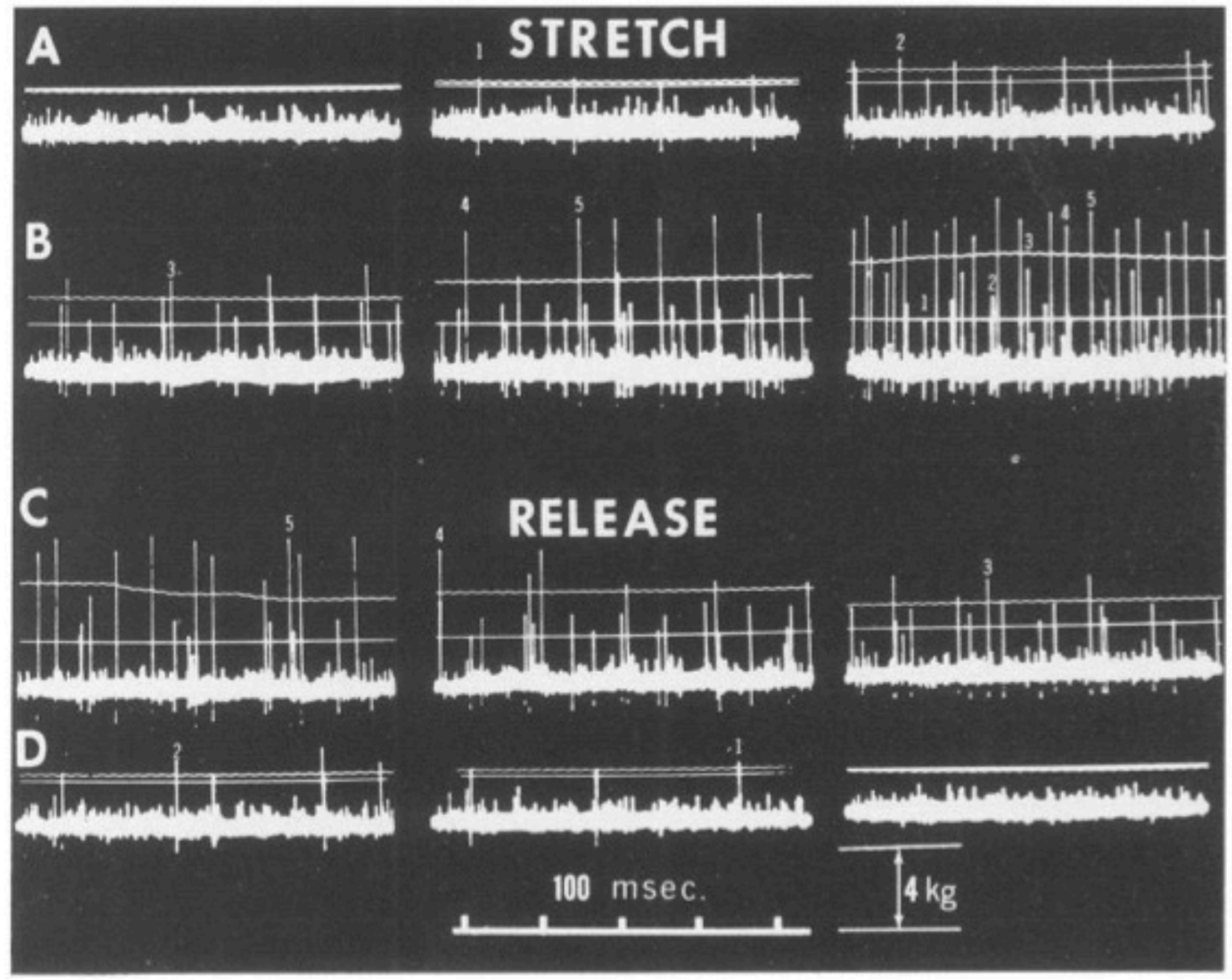


Motor unit redundancy

Elwood Henneman (1915-1996)

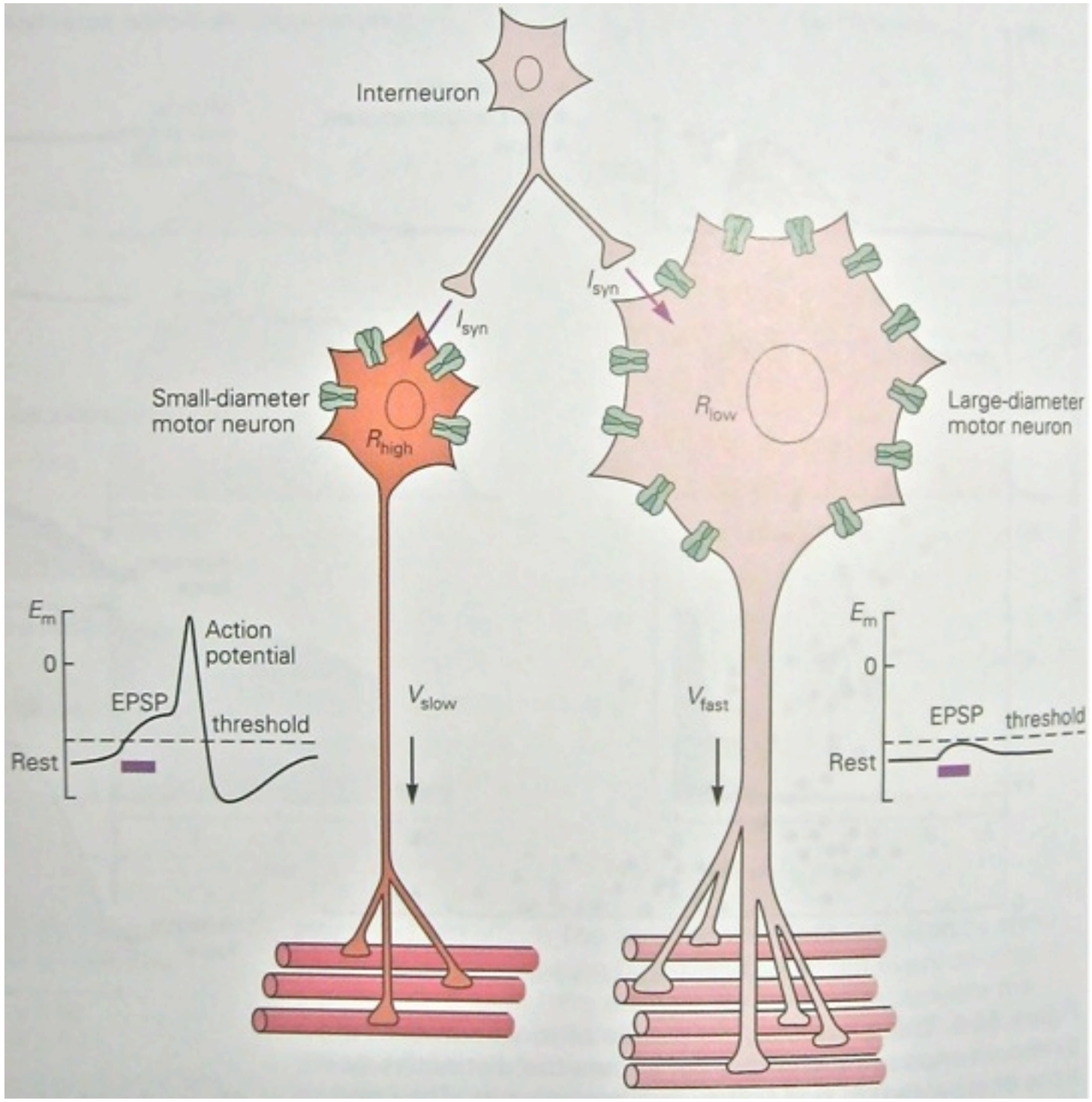


from Mendell, 2005



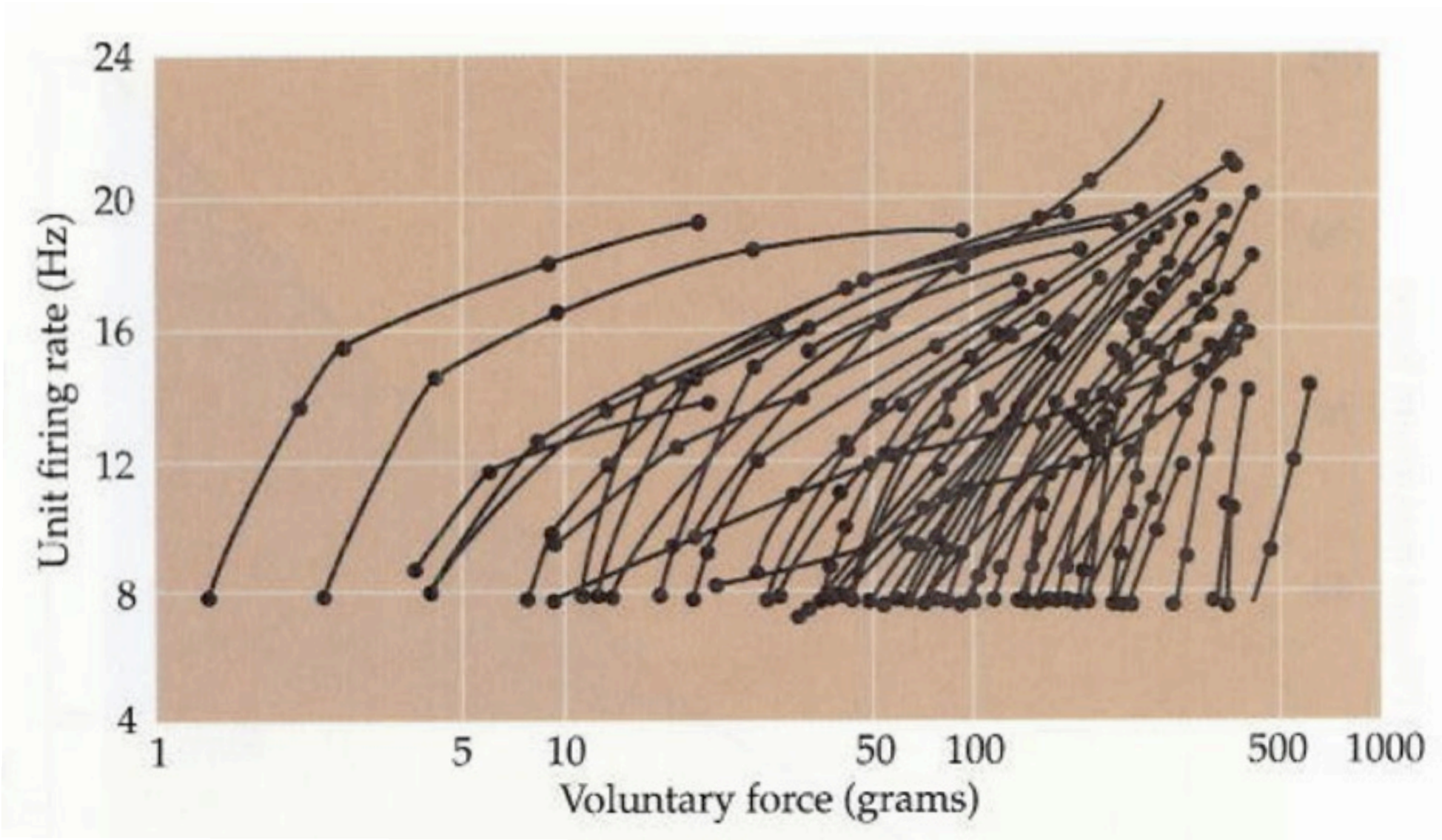
Henneman et al., 1965

Model of motor unit recruitment.



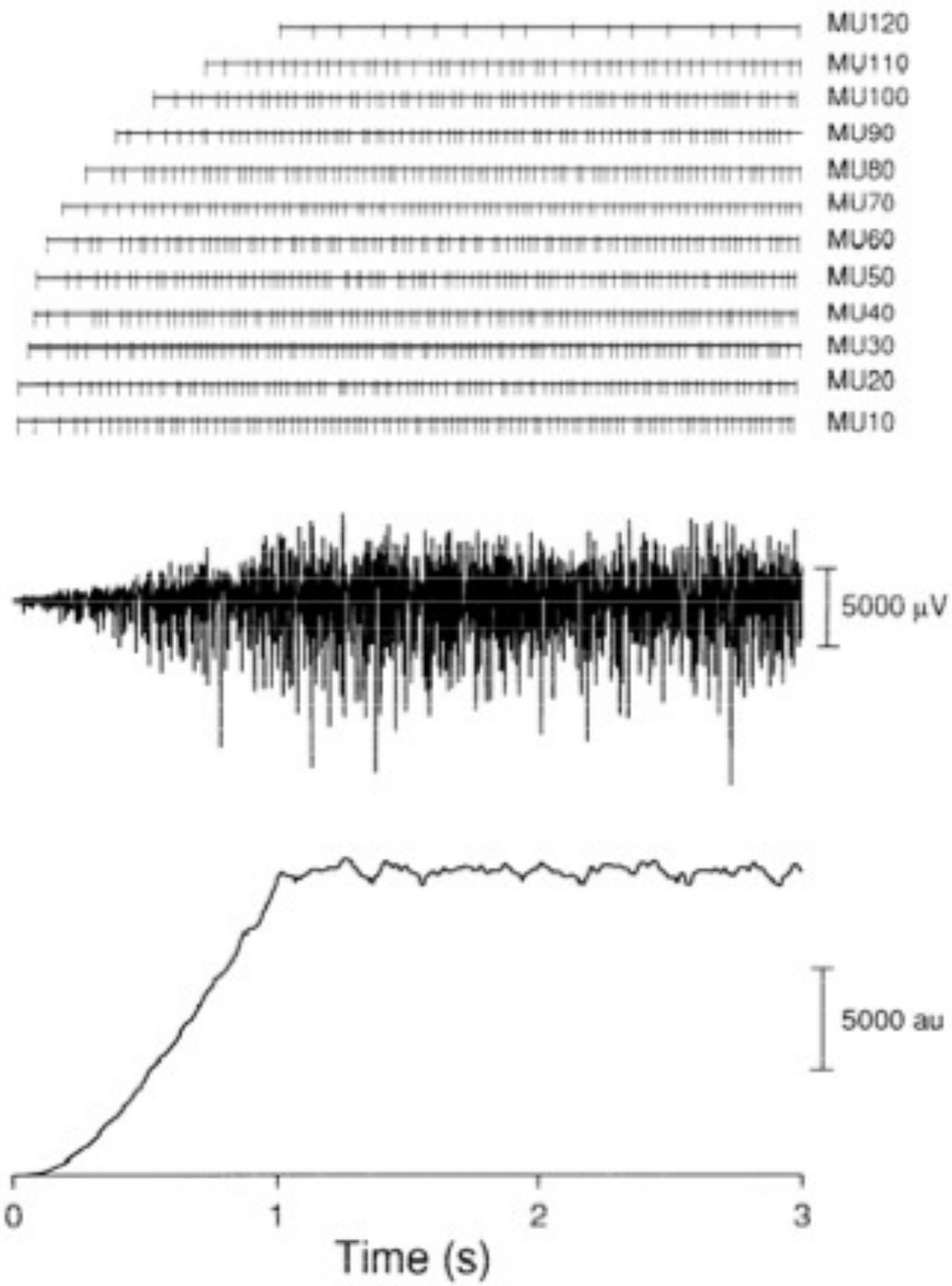
from Kandel, Schwartz, and Jessell, 4th ed.

Motor unit redundancy



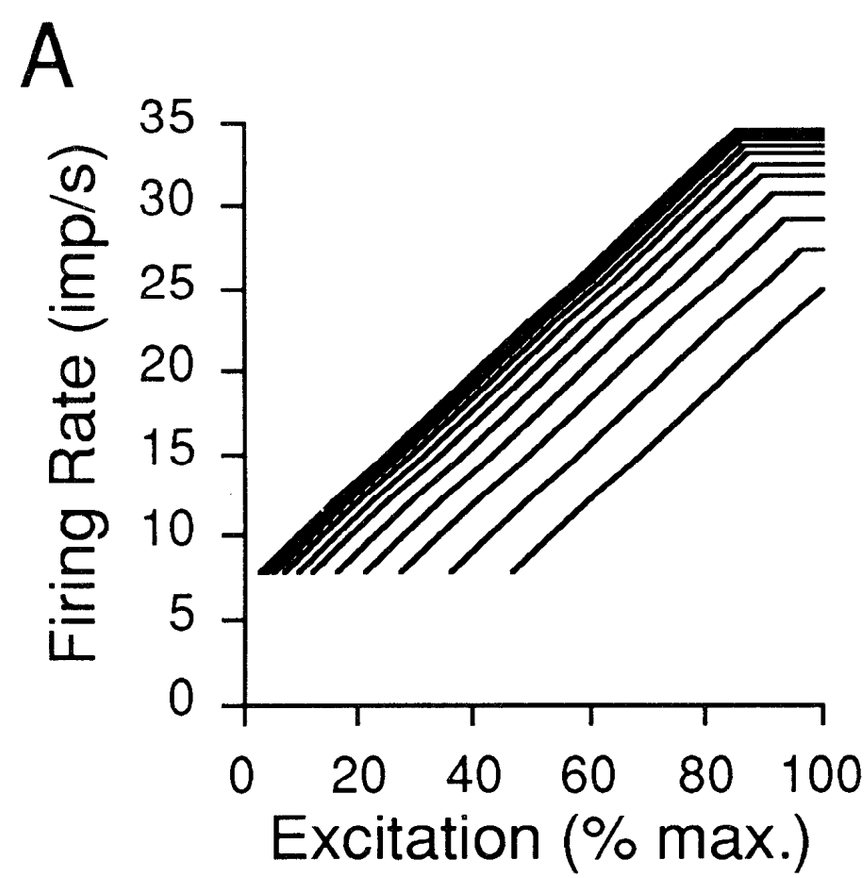
Monster and Chan, 1977, in Purves et al.

Motor unit redundancy



Ordered recruitment is built-in

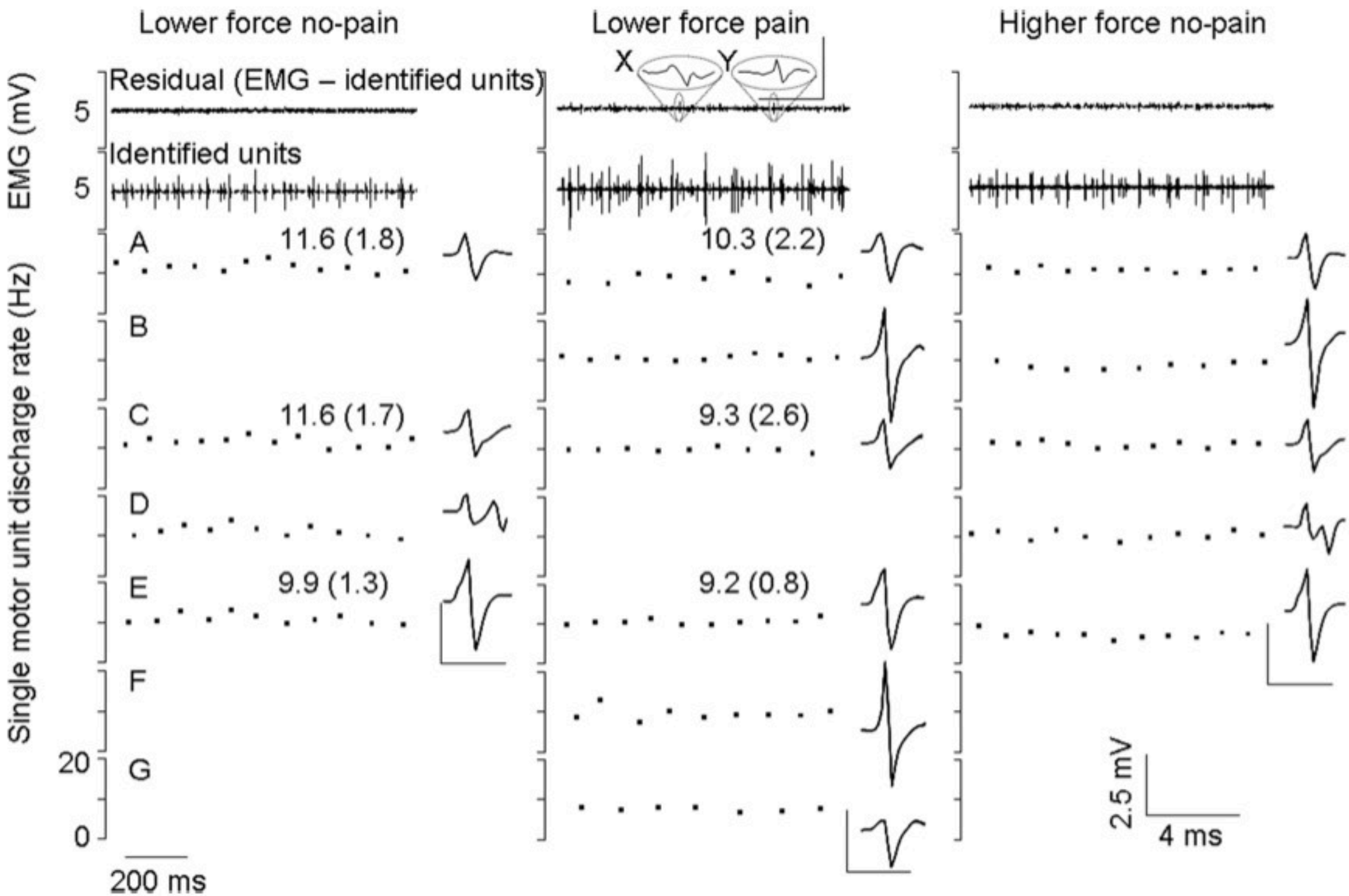
$$FR_i(t) = g_e \cdot [E(t) - RTE_i] + MFR \quad E(t) \geq RTE_i$$



Fuglevand et al. 1993

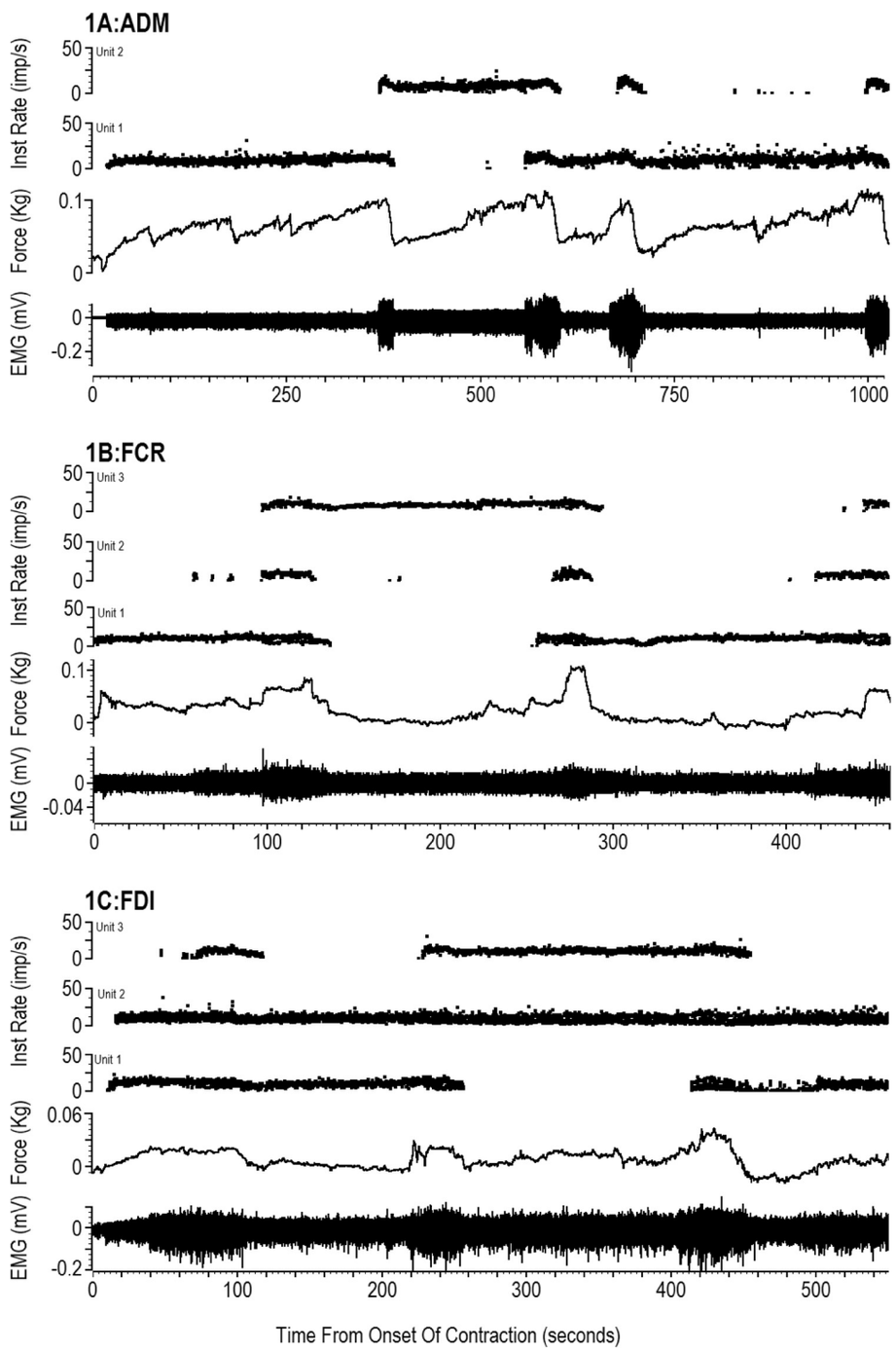
Fuglevand Model of Motor Unit Recruitment

Motor unit redundancy

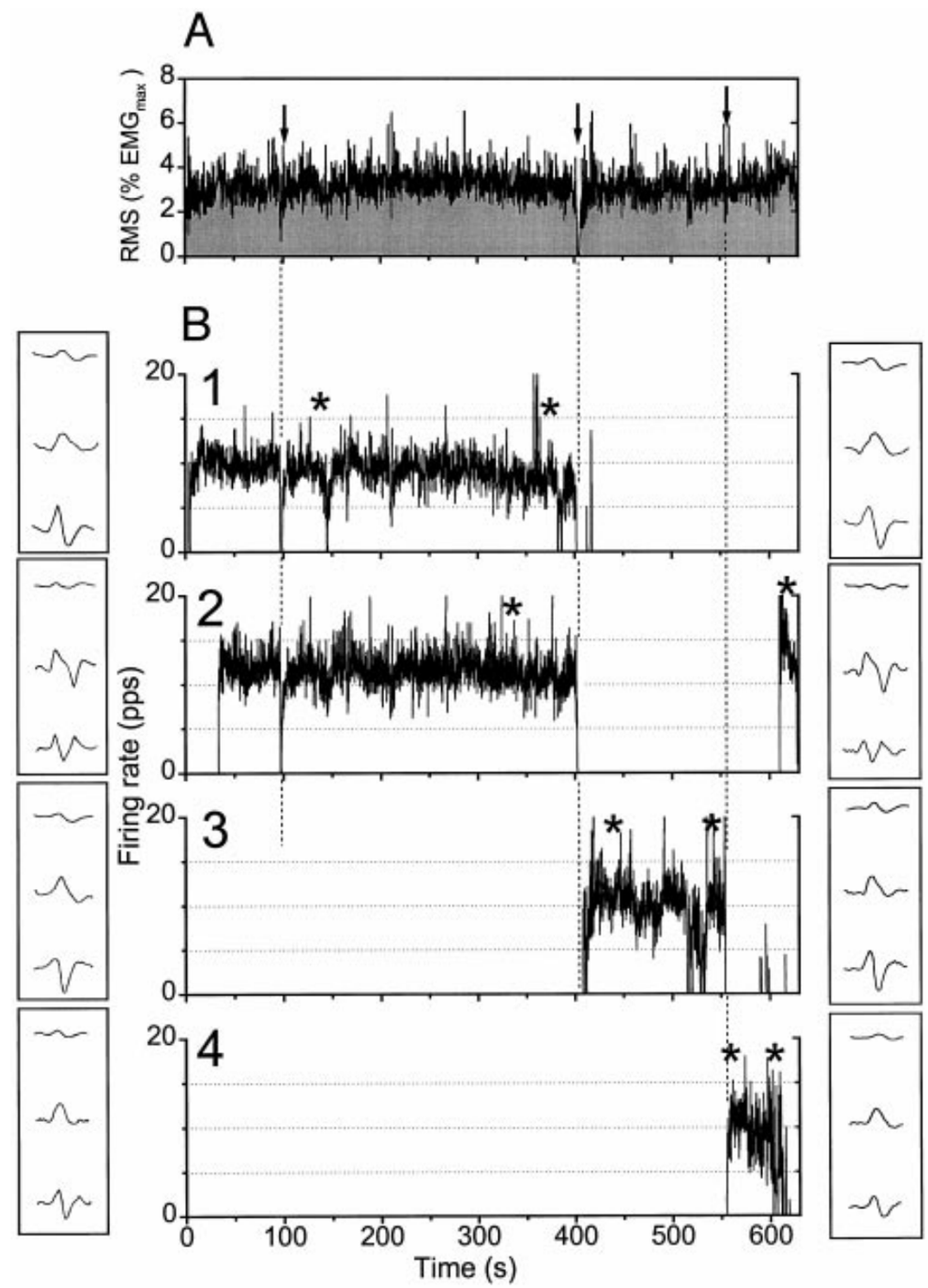


Tucker et al. 2009

Motor unit trade off during long contractions

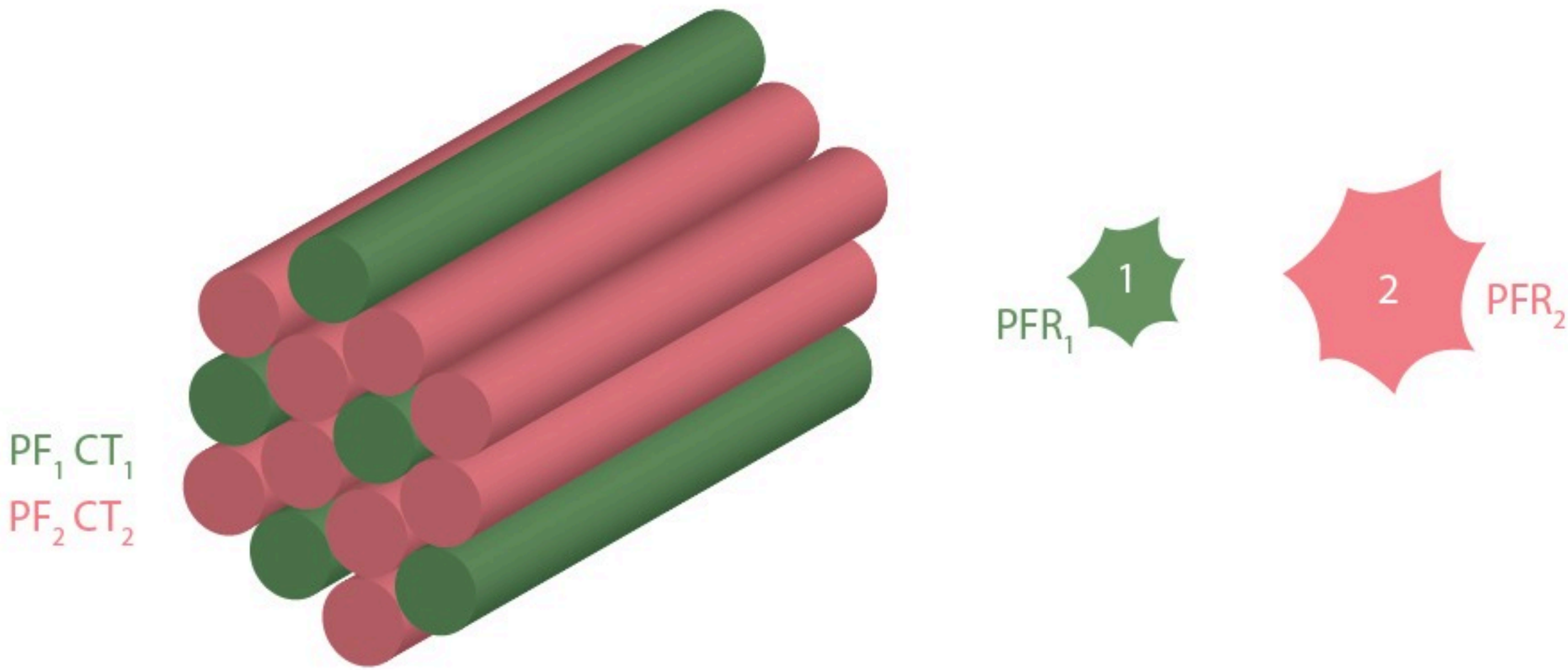


Bawa and Murnaghan, 2009

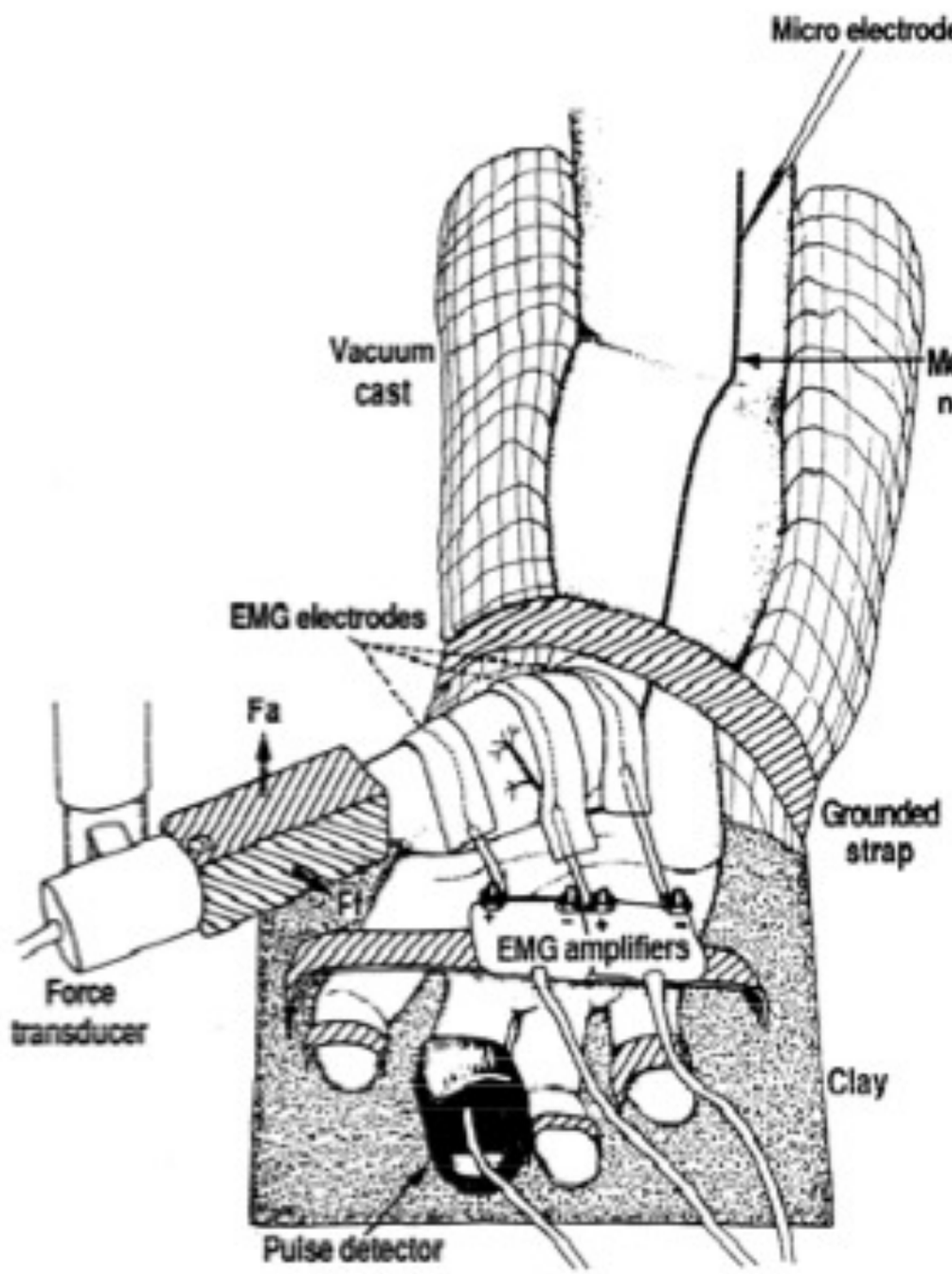


Westgaard and De Luca, 1999

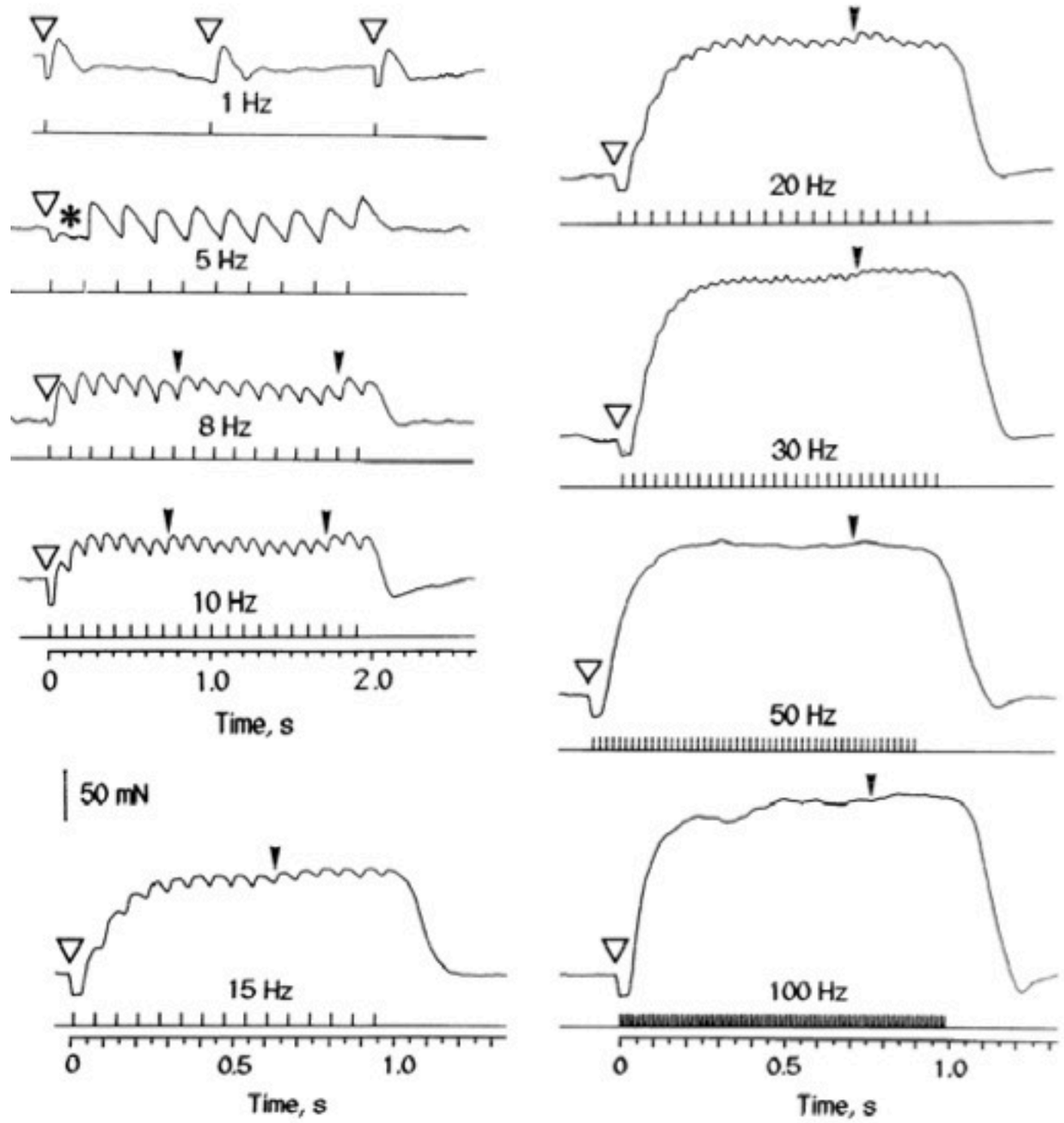
Computationally describing the motor unit pool requires mechanical and neural parameters



Motor unit redundancy

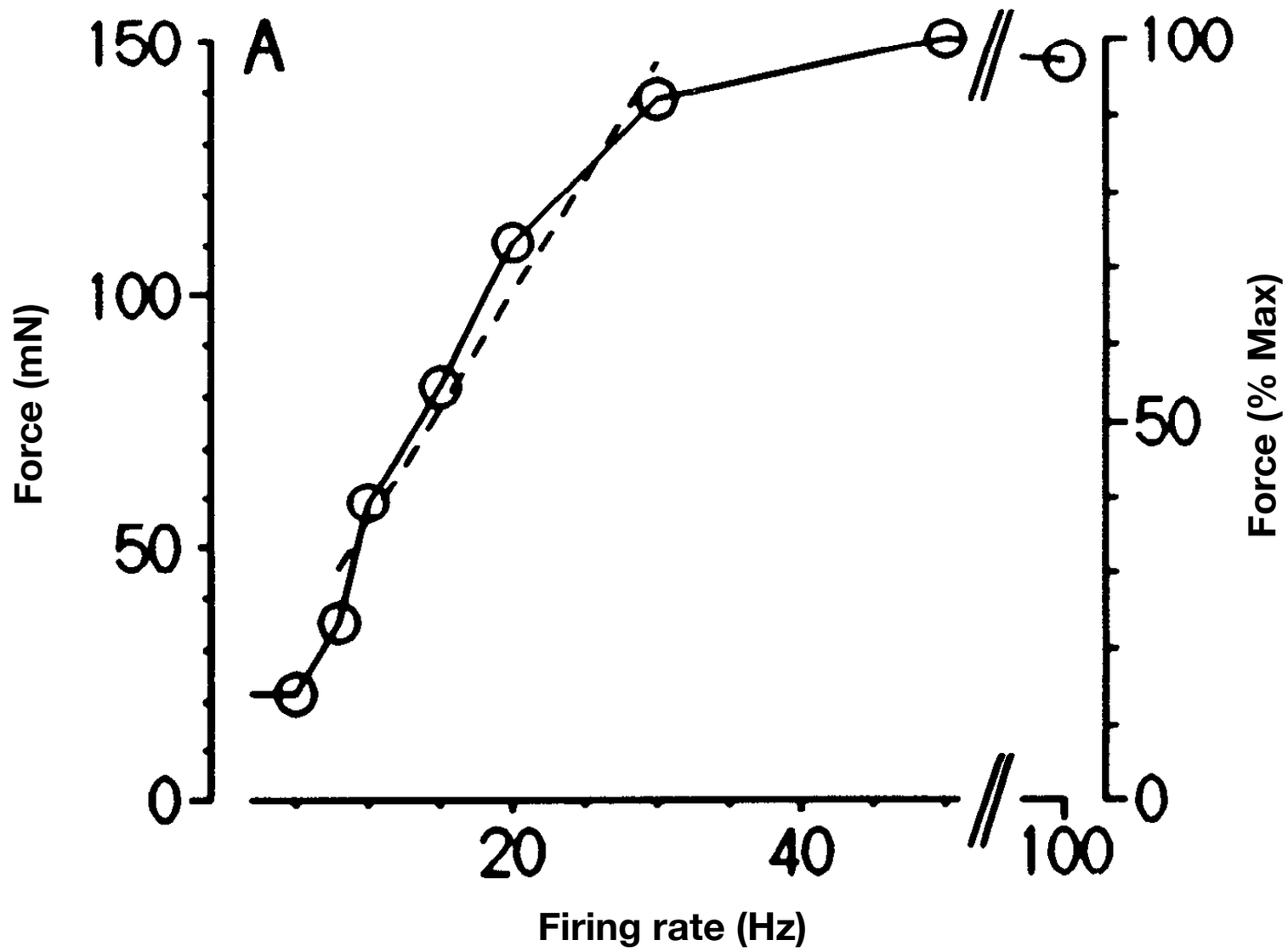


Westling et al. 1990

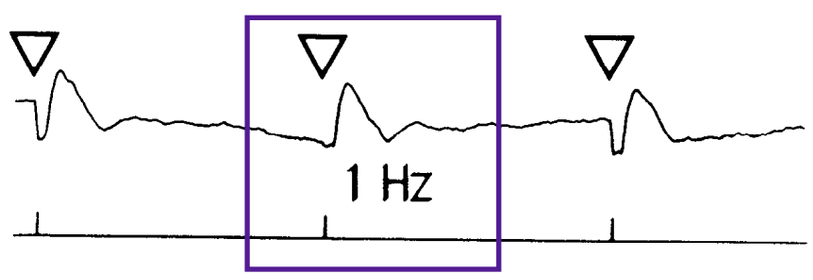


Thomas et al. 1991

Motor unit redundancy



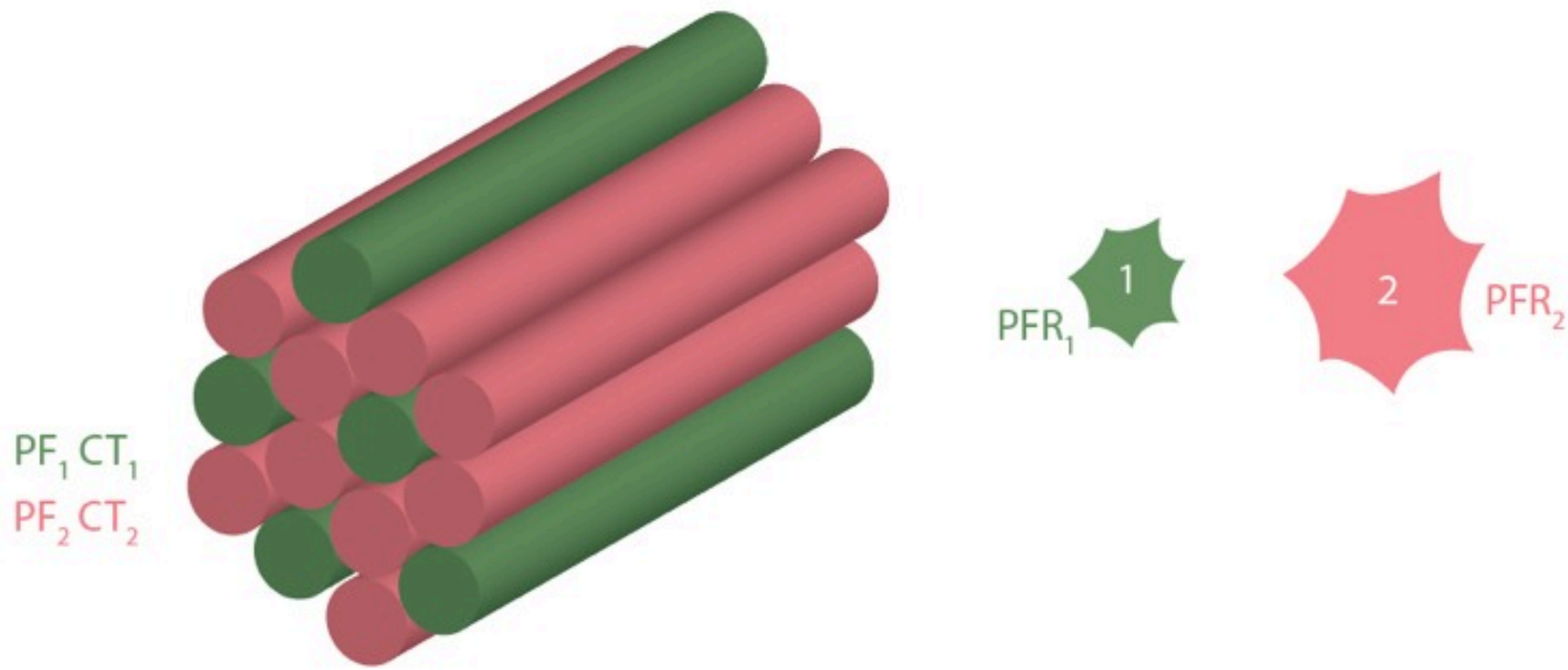
Thomas et al., 1991



$$T(t) = \frac{eP}{C} t e^{-t/C}$$

$$F_{ss} = ePCf$$

Unlike optimizing muscle use, optimizing motor unit use is MINLP (NP hard)



Minimize Energy Expenditure over variables f and a, subject to

$$eP_1C_1f_1a_1 + eP_2C_2f_2a_2 + \cdots + eP_nC_nf_na_n = F_d$$

$$f_i < PFR_i$$

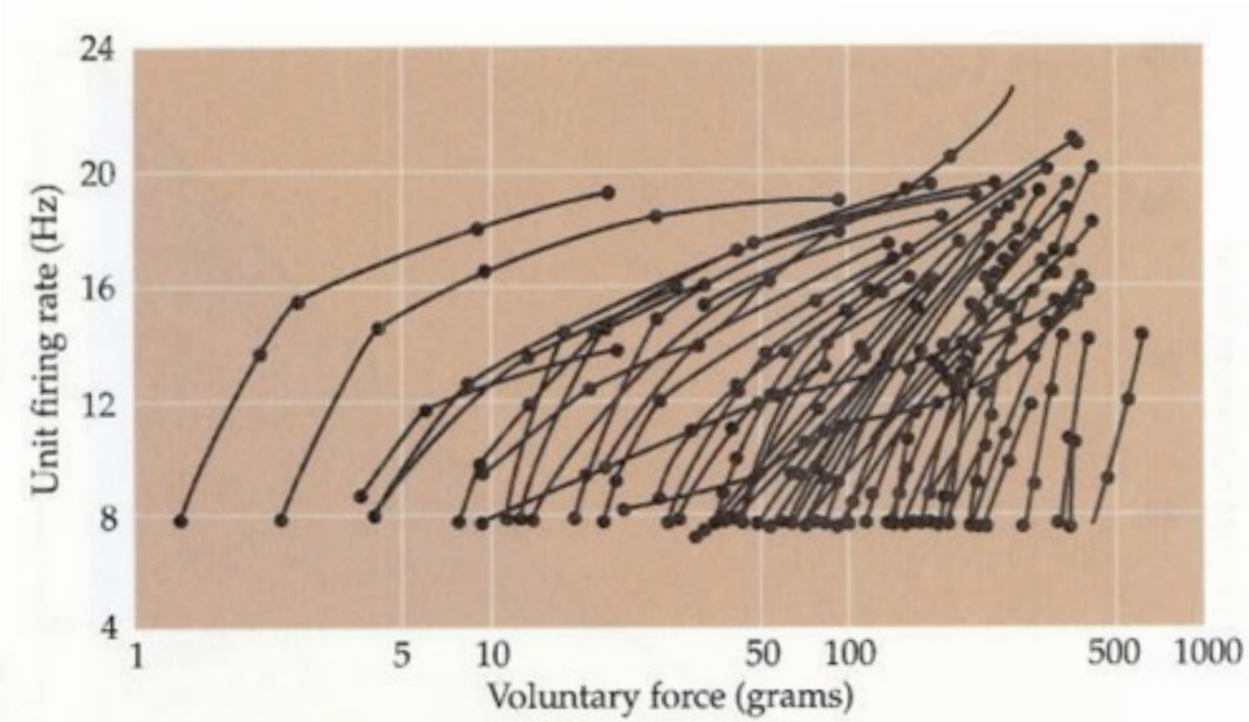
$$a_i \text{ is either } 0 \text{ or } 1$$

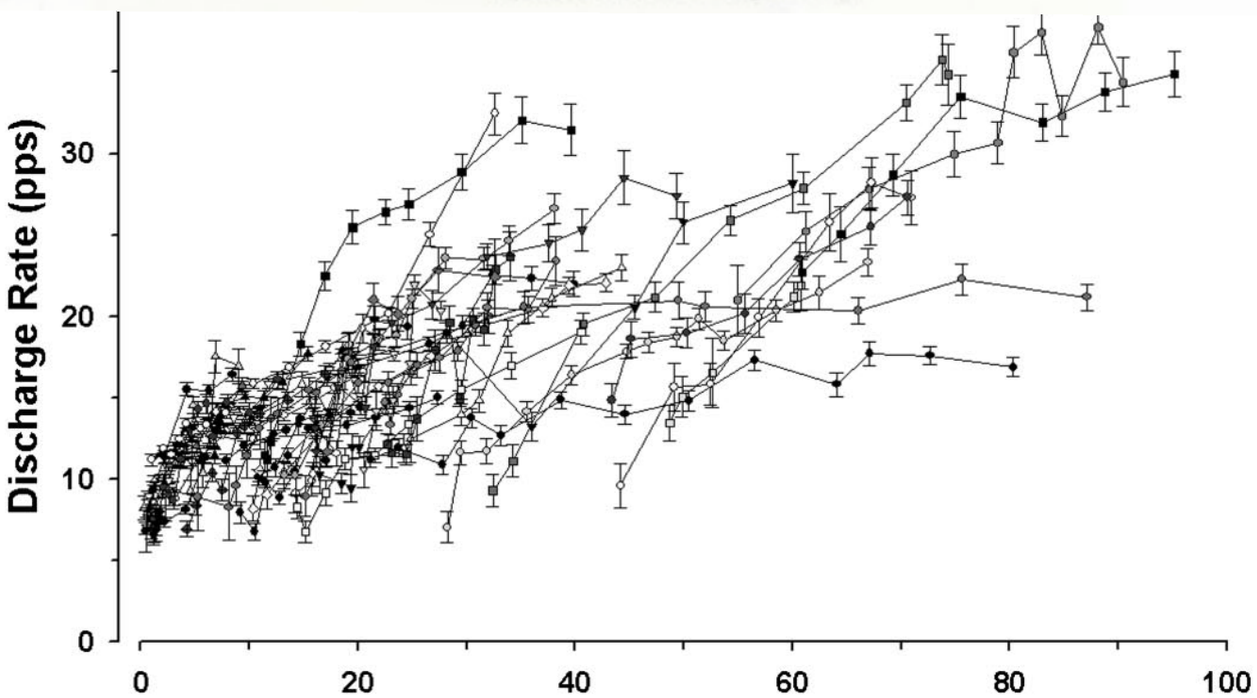
Mixed integer nonlinear optimization (MINLP)

MINLP Model of Motor Unit Recruitment

Kutch et al., *In preparation*

Motor unit redundancy

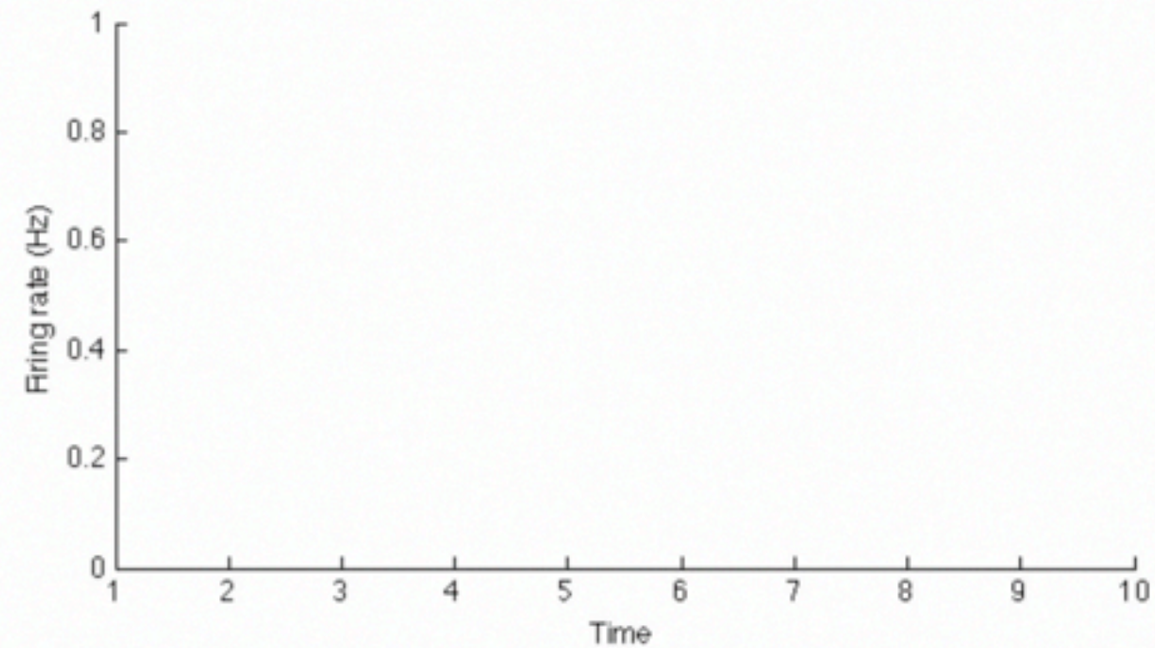


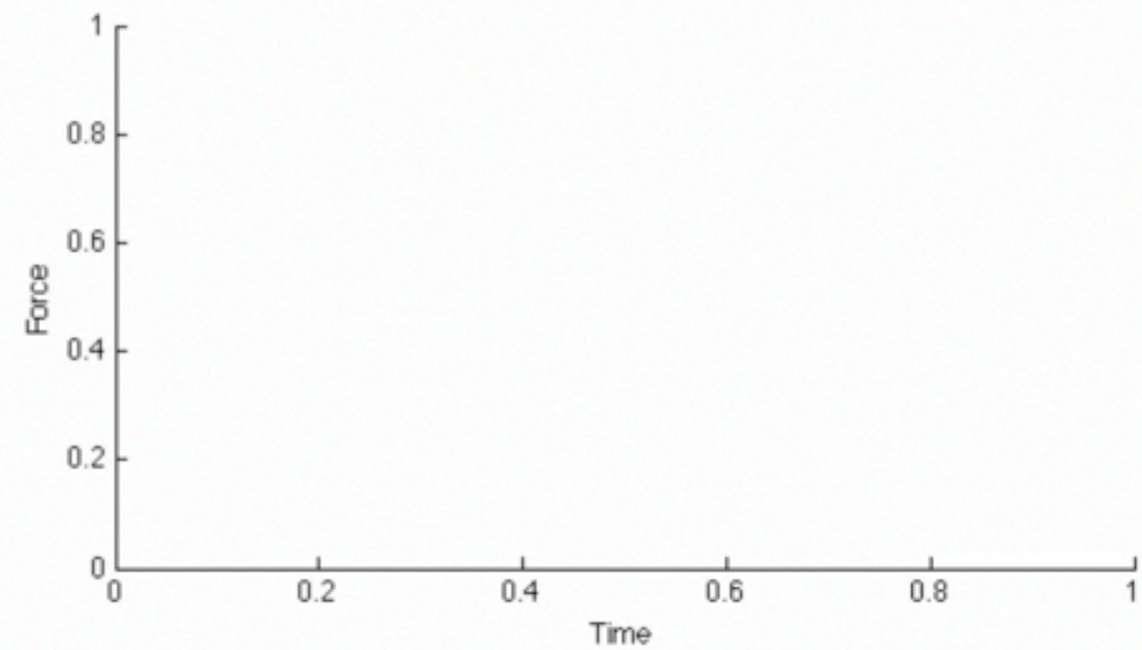


Monster and Chan, 1977, in Purves et al.

Moritz et al., 2005

MINLP solution





Motor unit rotation: depletion recharge model

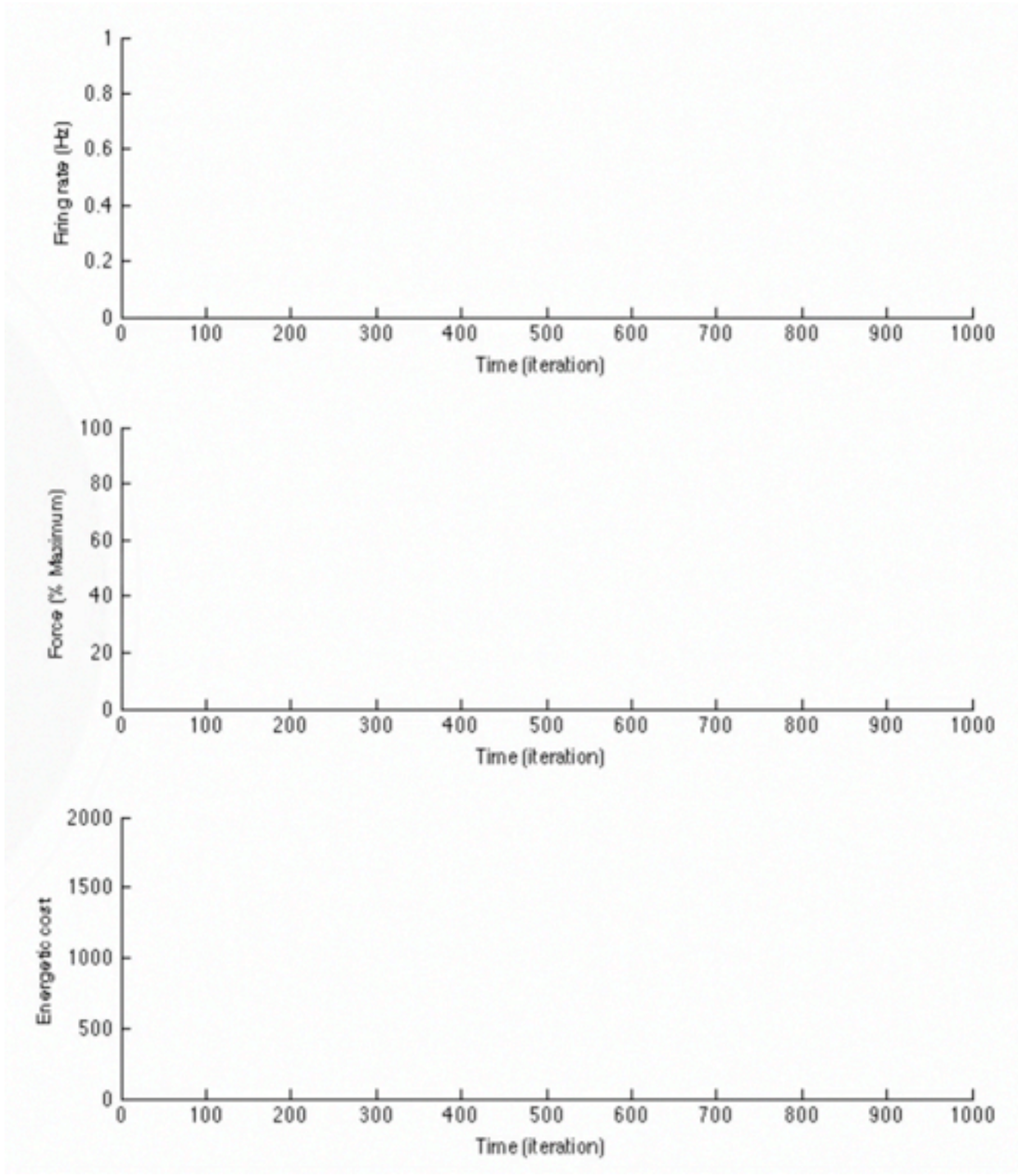
1. If motor unit active, peak firing rate decays
2. If motor unit is off, peak firing rate recovers
3. When peak firing rate passes a threshold, motor unit is ready to go again

see Dideriksen et al., 2010 for a more complex model

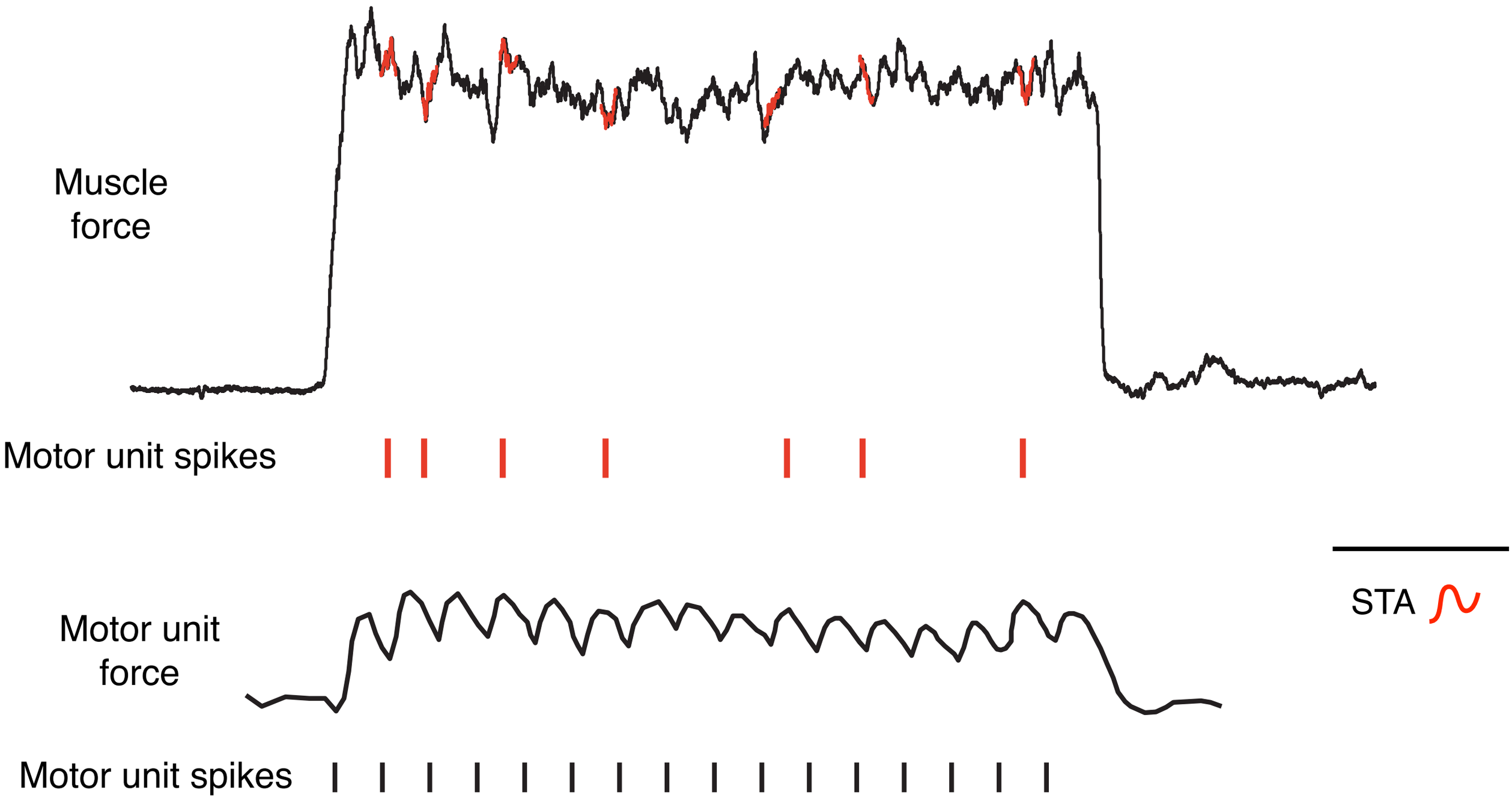
MINLP Model of Motor Unit Rotation

Kutch et al., *In preparation*

Simulated motor unit rotation: 5% maximum

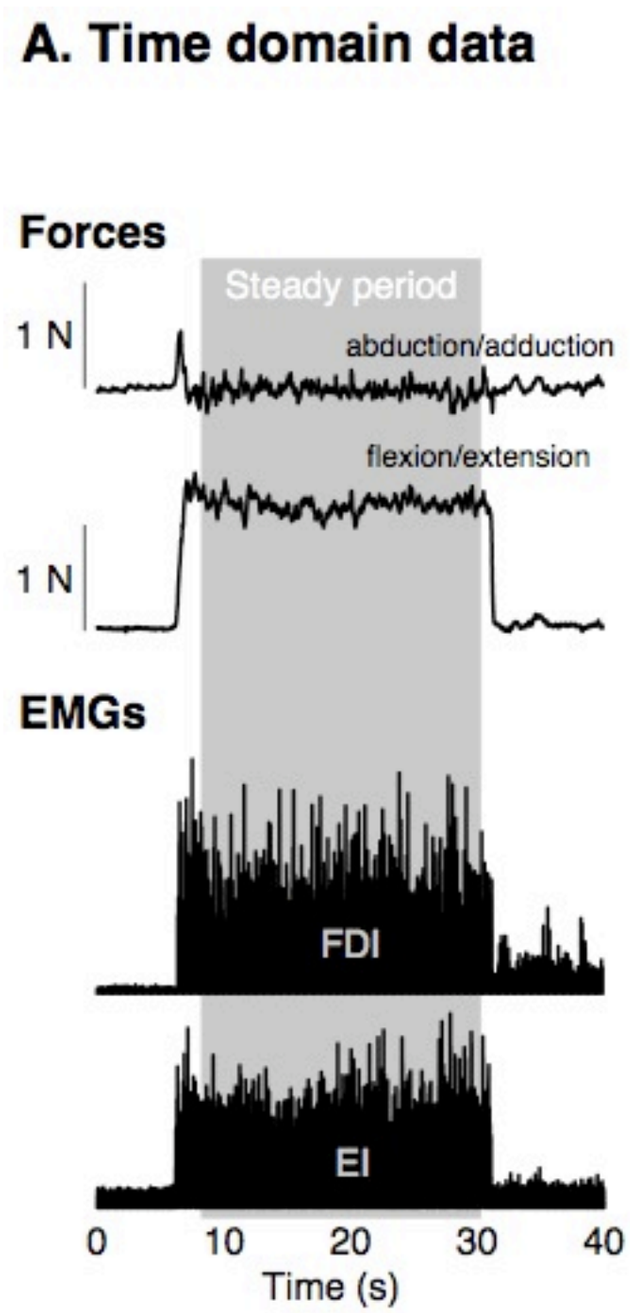


Spike triggered averaging: information from “noise”



Stein et al., 1972
Kutch et al., 2007

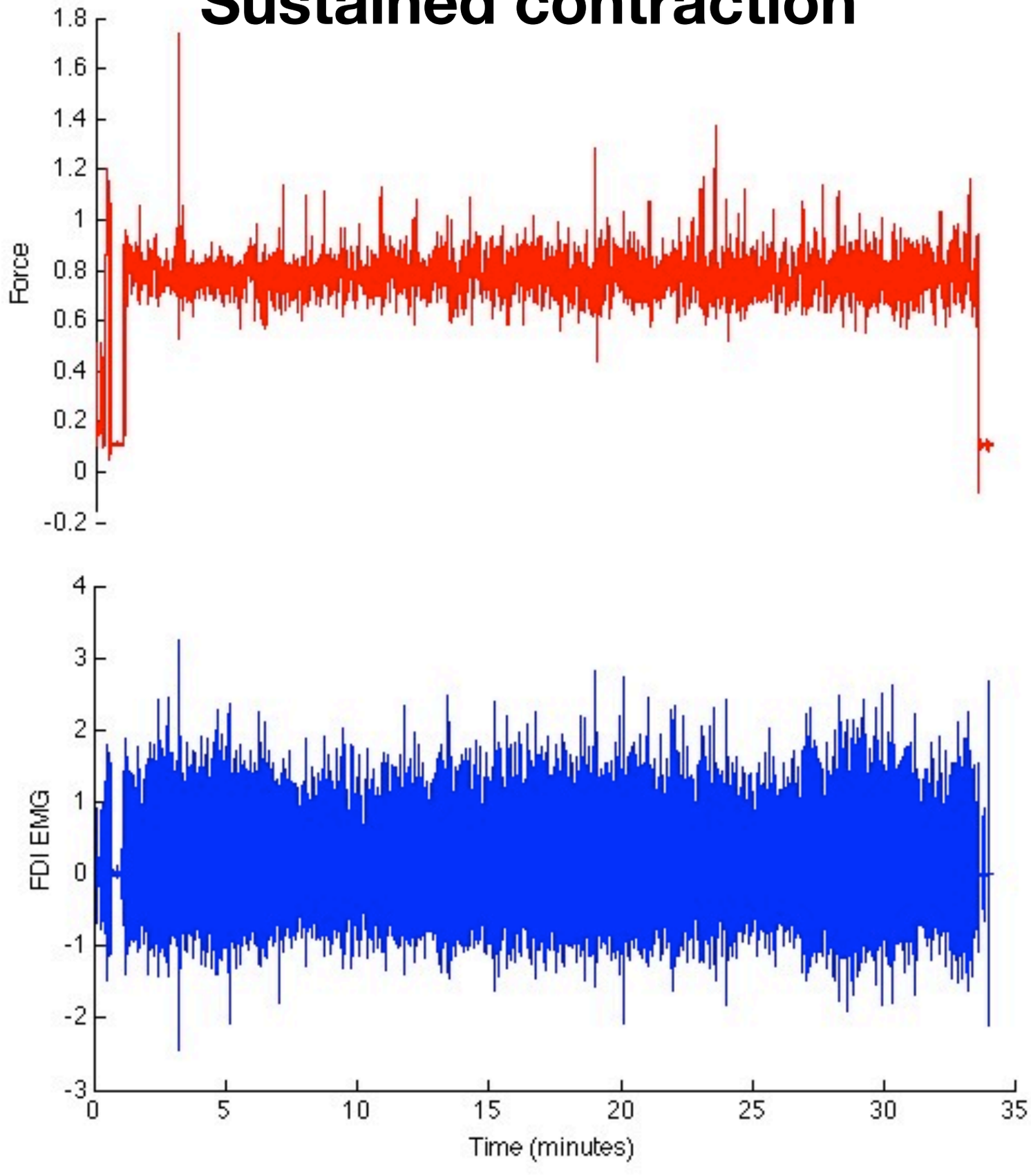
EMG-weighted averaging (EWA)



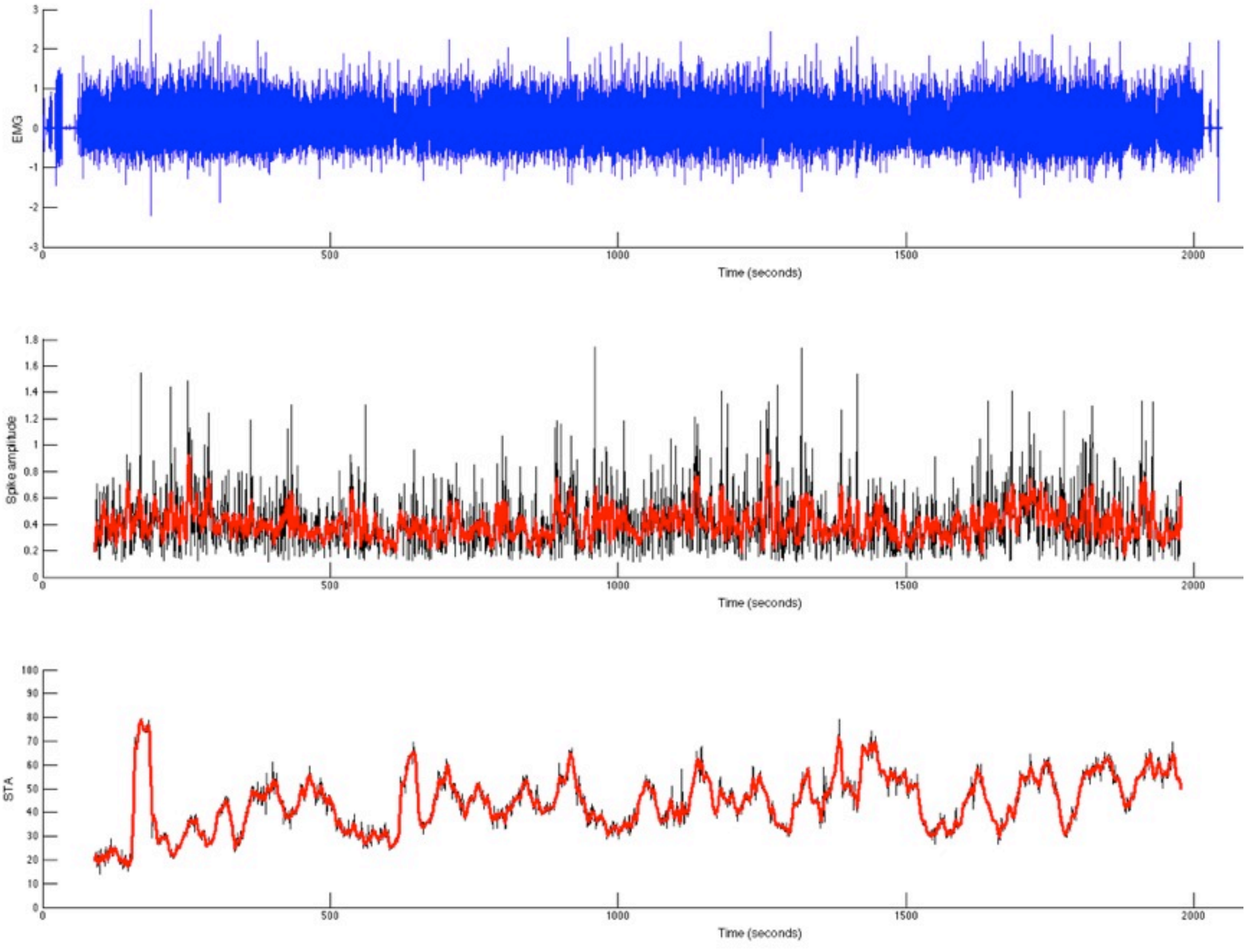
Kutch et al., 2010

Motor unit redundancy

Sustained contraction



Evidence of motor unit rotation



Fuglevand Model of Spike-triggered Averaging

Summary

1. Understanding and better treating chronic pain is essential. Problem of brain-body interaction?

2. Examples of subconscious peripheral activity oscillations from *muscle redundancy*

3. Examples of subconscious peripheral activity oscillations from *motor unit redundancy*

4. Utility of doing experiments but thinking about them using simple models.

Thank you